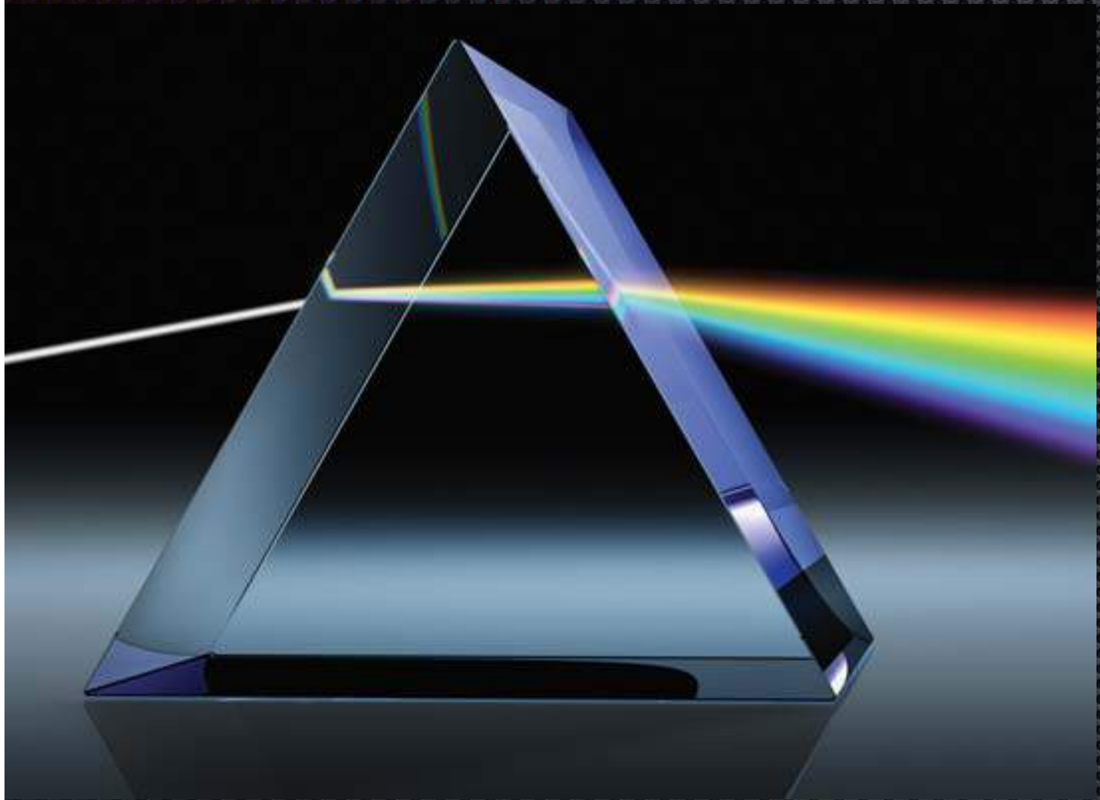
SouLMan

http://web.nano.cnr.it/SoulMan

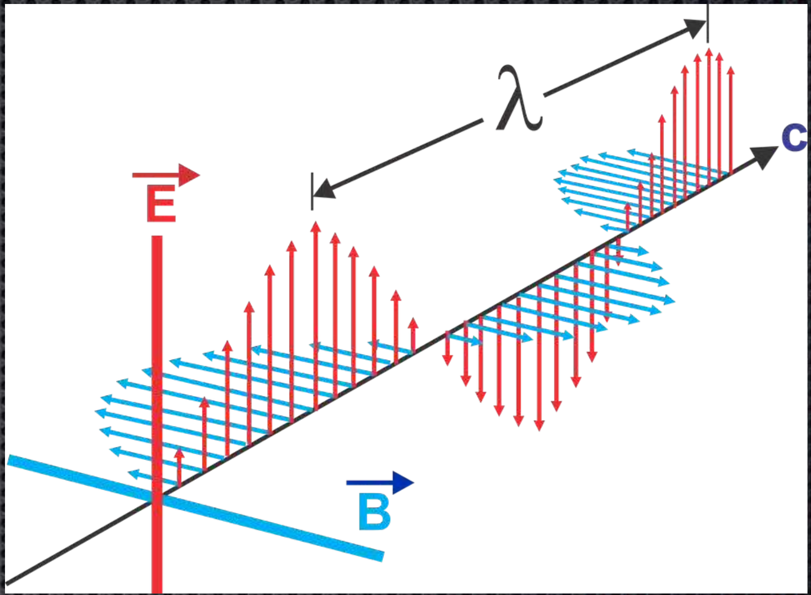
Disegnare la luce: la fotonica con i nanomateriali.

Alessandro Tredicucci
Dipartimento di Fisica “Enrico Fermi”
Università di Pisa

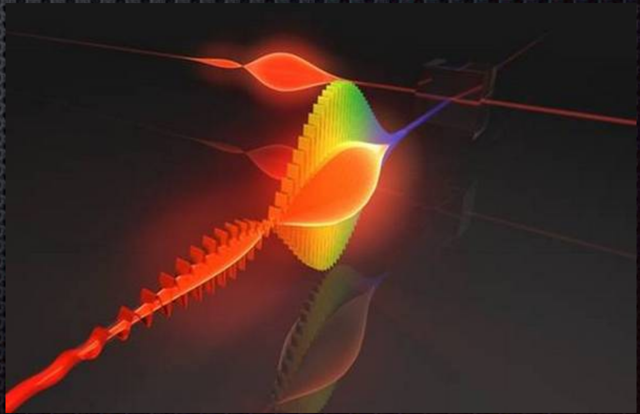
Che cos'è la luce?



Particella: i fotoni
Il numero di fotoni ci dice quanto è intensa la radiazione



Onda elettromagnetica



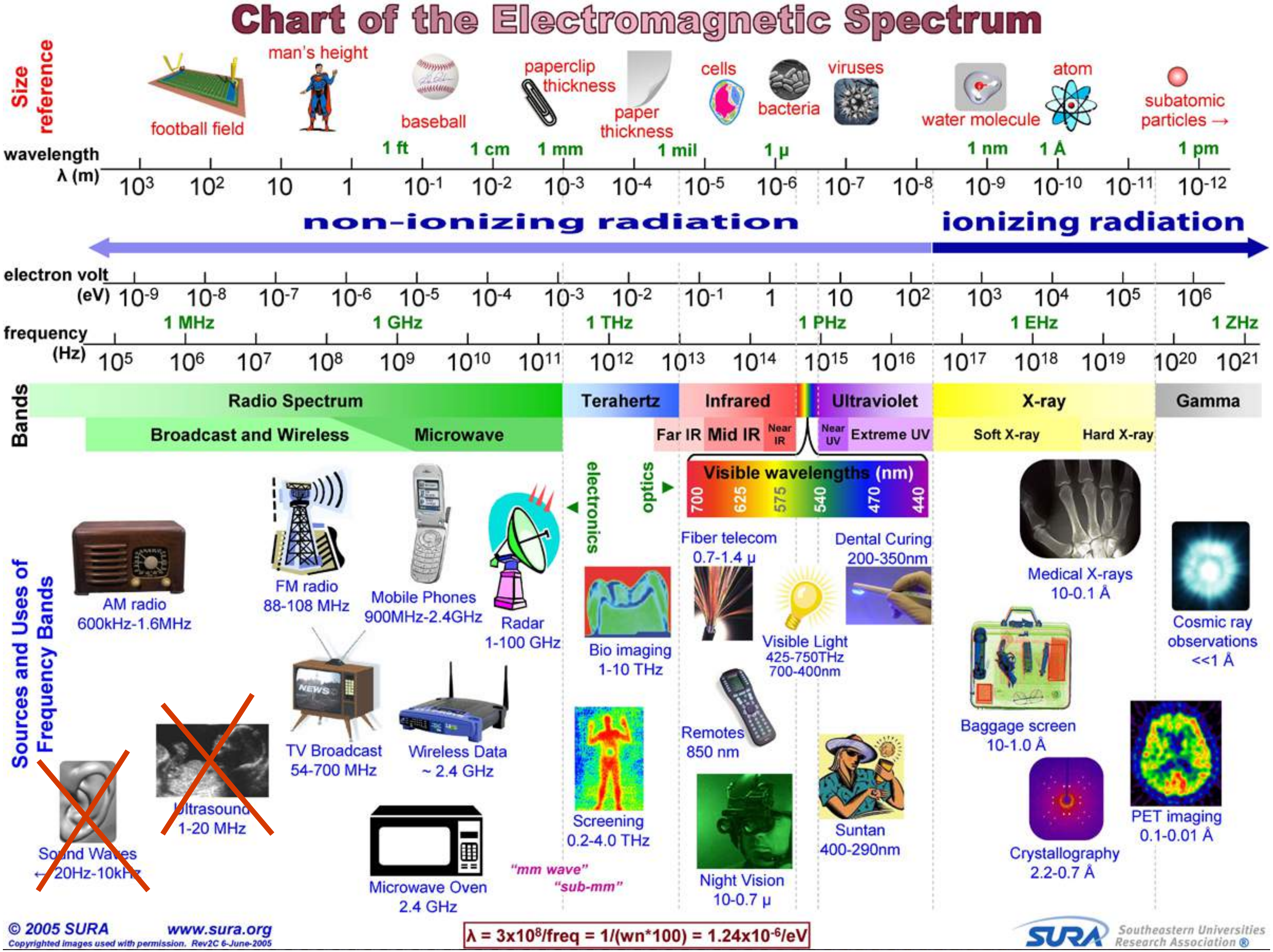


Chart of the Electromagnetic Spectrum
Size reference
football field
man's height
baseball
paperclip thickness
paper thickness
cells
bacteria
viruses
water molecule
atom
subatomic particles →
wavelength λ (m)
1 ft
1 cm
1 mm
1 mil
1 μ
1 nm
1 Å
1 pm
10^3 10^2 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
non-ionizing radiation
ionizing radiation
electron volt (eV)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6
frequency (Hz)
1 MHz
1 GHz
1 THz
1 PHz
1 EHz
1 ZHz
10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21}
Bands
Radio Spectrum
Broadcast and Wireless
Microwave
Terahertz
Infrared
Far IR
Mid IR
Near IR
Ultraviolet
Near UV
Extreme UV
X-ray
Soft X-ray
Hard X-ray
Gamma
electronics
optics
Visible wavelengths (nm)
700 625 575 540 470 440
Sources and Uses of Frequency Bands
AM radio 600kHz-1.6MHz
FM radio 88-108 MHz
Mobile Phones 900MHz-2.4GHz
Radar 1-100 GHz
TV Broadcast 54-700 MHz
Wireless Data ~ 2.4 GHz
Microwave Oven 2.4 GHz
Sound Waves ←20Hz-10kHz
Ultrasound 1-20 MHz
"mm wave"
"sub-mm"
Bio imaging 1-10 THz
Screening 0.2-4.0 THz
Fiber telecom 0.7-1.4 μ
Visible Light 425-750THz 700-400nm
Remotes 850 nm
Night Vision 10-0.7 μ
Dental Curing 200-350nm
Suntan 400-290nm
Medical X-rays 10-0.1 Å
Baggage screen 10-1.0 Å
Crystallography 2.2-0.7 Å
Cosmic ray observations <<1 Å
PET imaging 0.1-0.01 Å
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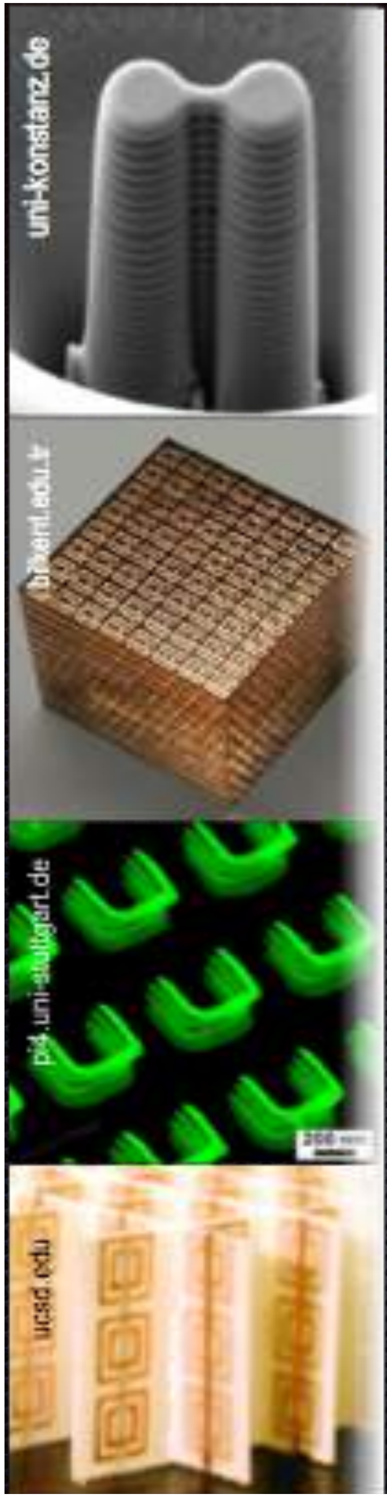
www.sura.org
Copyrighted images used with permission. Rev2C 6-June-2005
$\lambda = 3x10^8/freq = 1/(wn*100) = 1.24x10^{-6}/eV$
SURA Southeastern Universities Research Association ®



Photon engineering

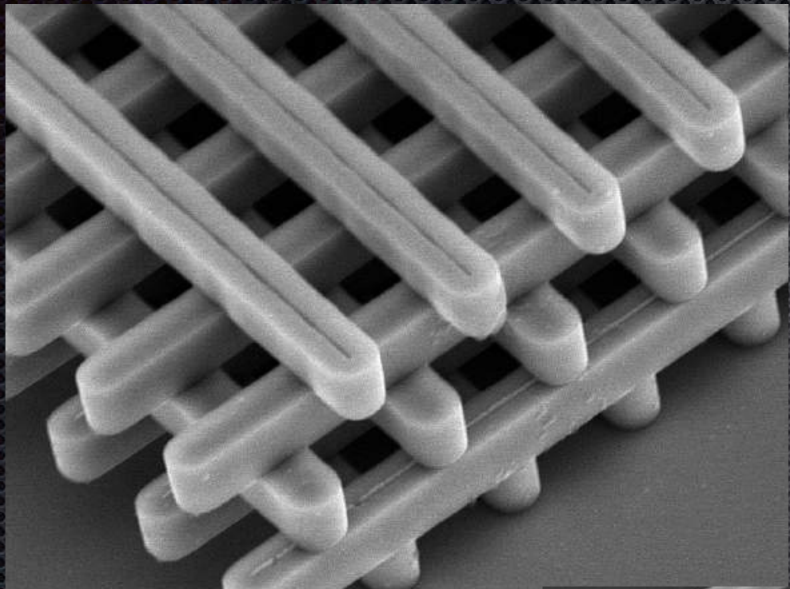
Paradigma dell’ottica moderna: “disegnare” il modo in cui la radiazione interagisce con la materia

Idea: strutture sub-wavelength microcavità, cristalli fotonici, metamateriali

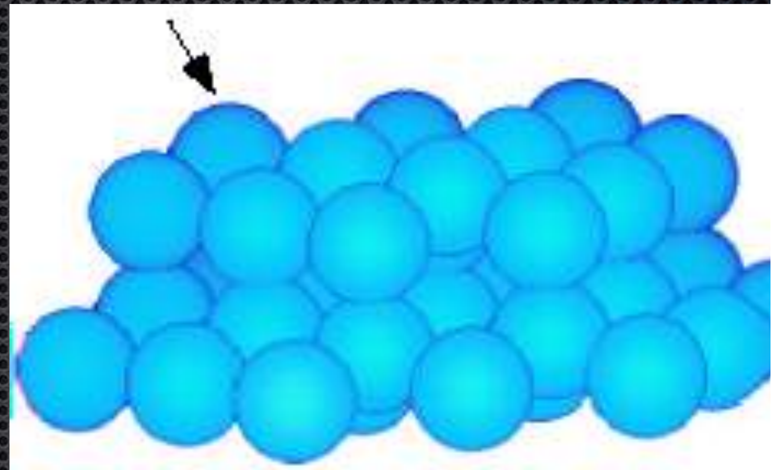
Controllo in “quattro” dimensioni

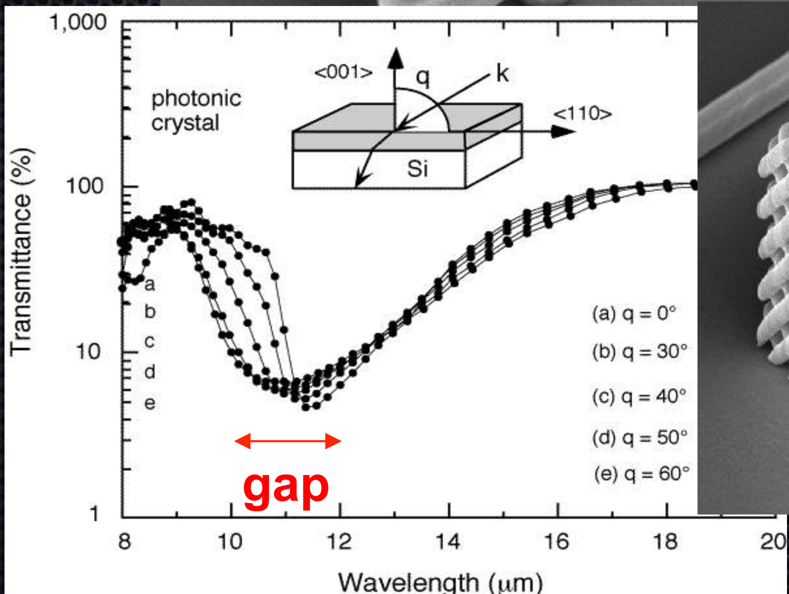
Esaltare l’interazione

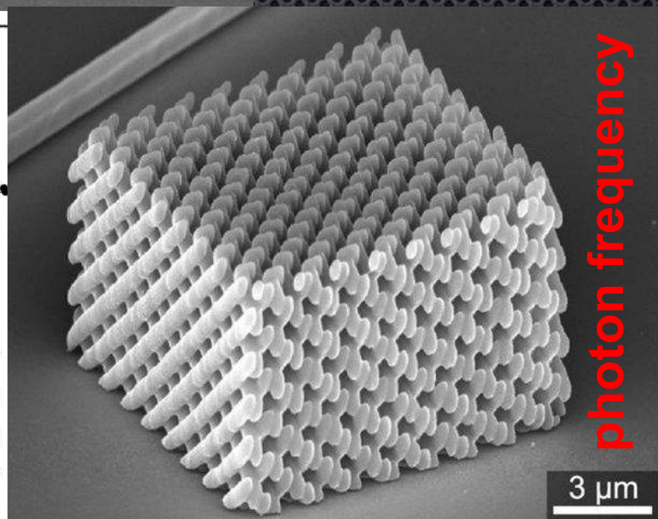
Cristalli Fotonici

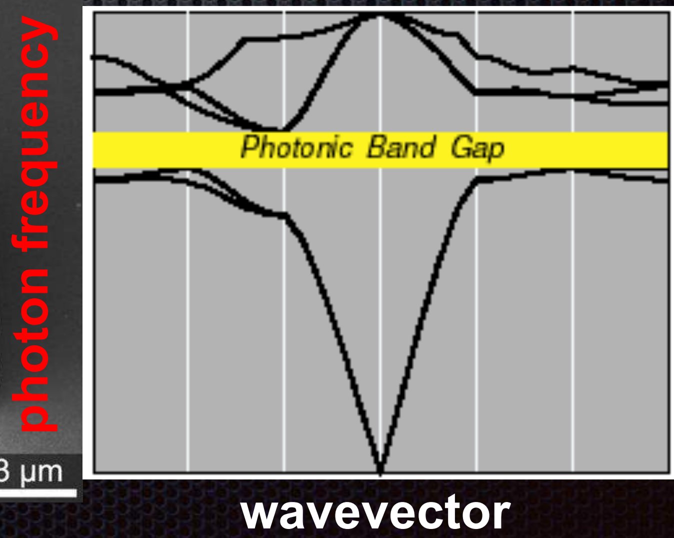


dielectric spheres, diamond latti

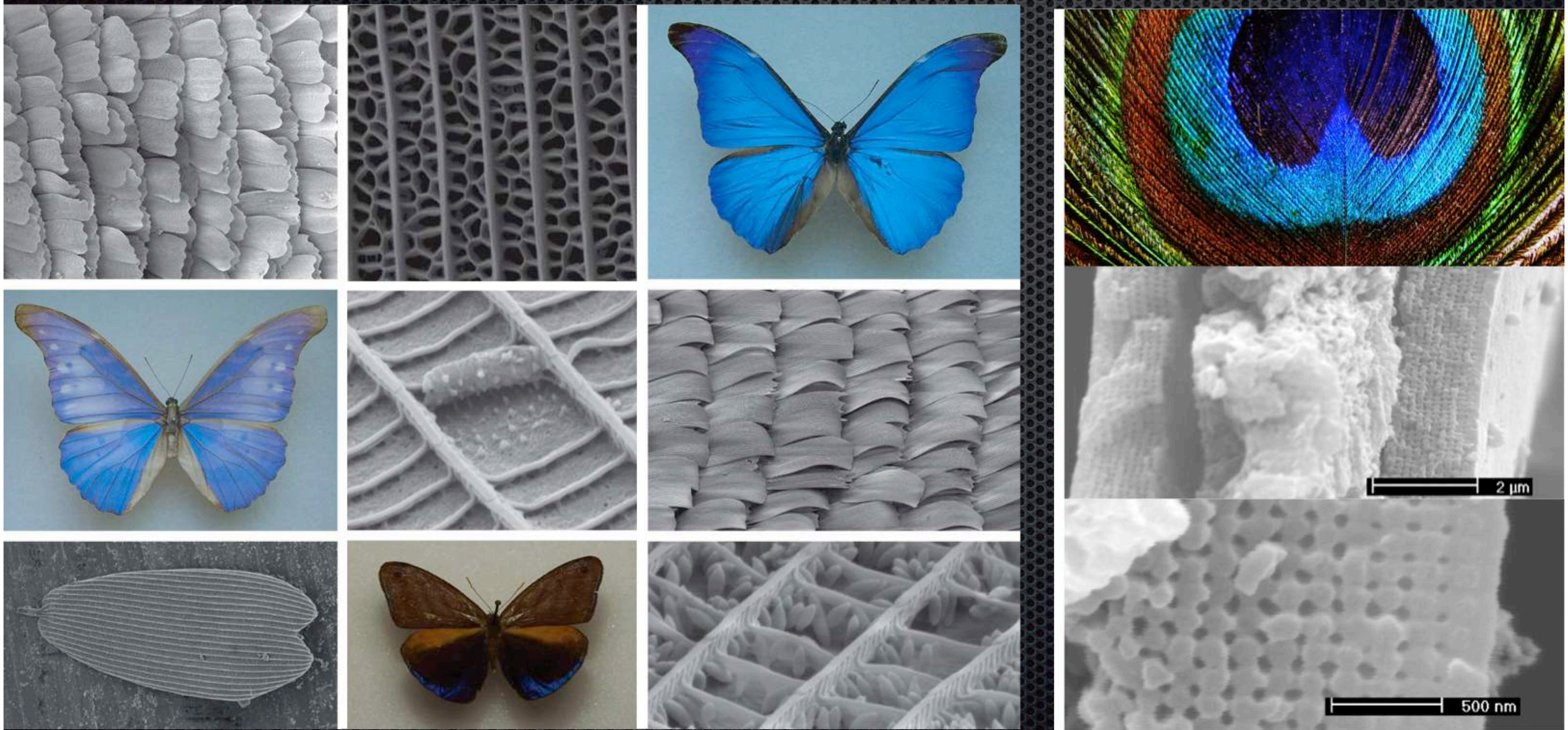




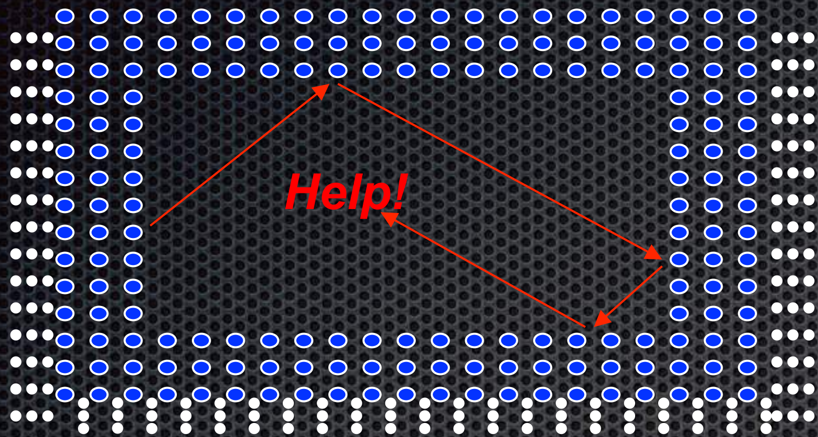


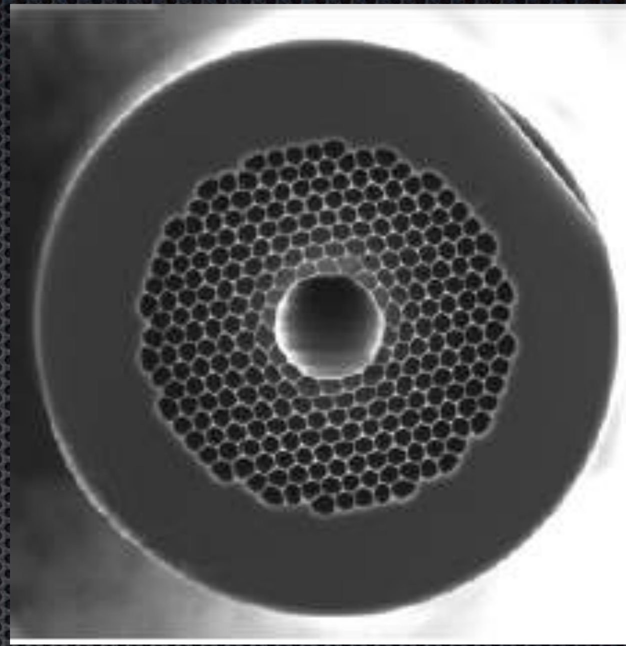


Cristalli fotonici naturali

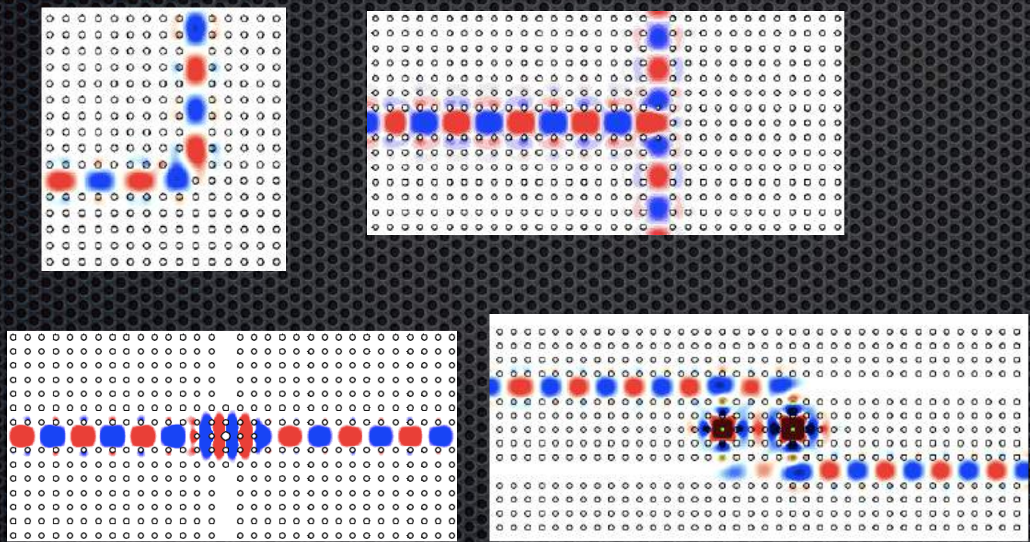


Applicazioni

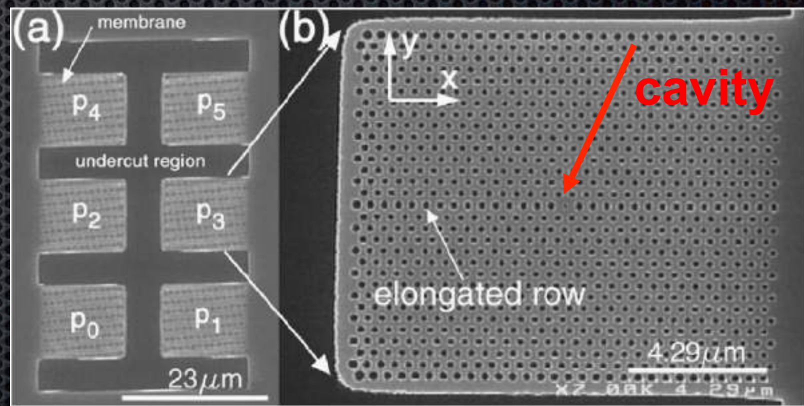




Fibre ottiche

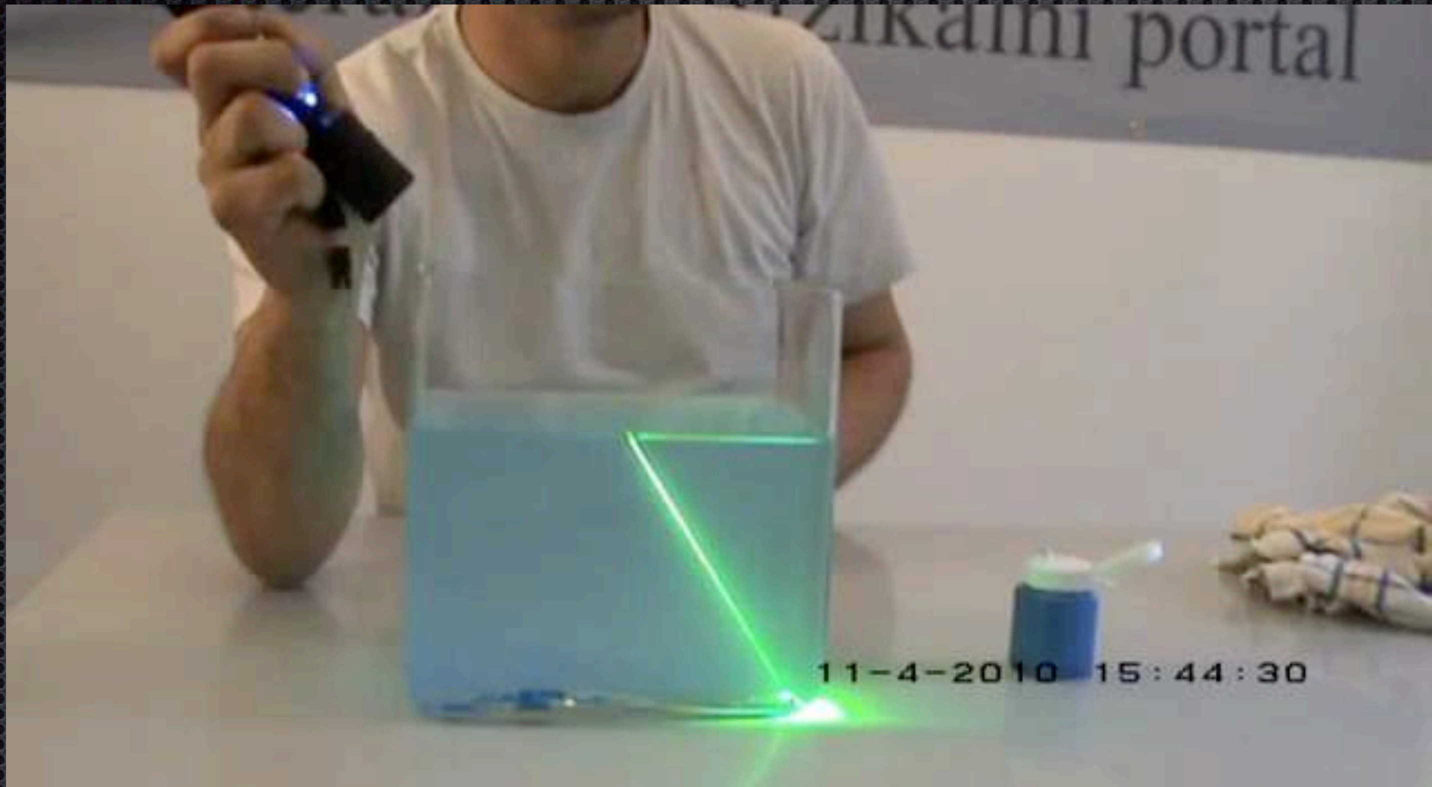


Ottica guidata



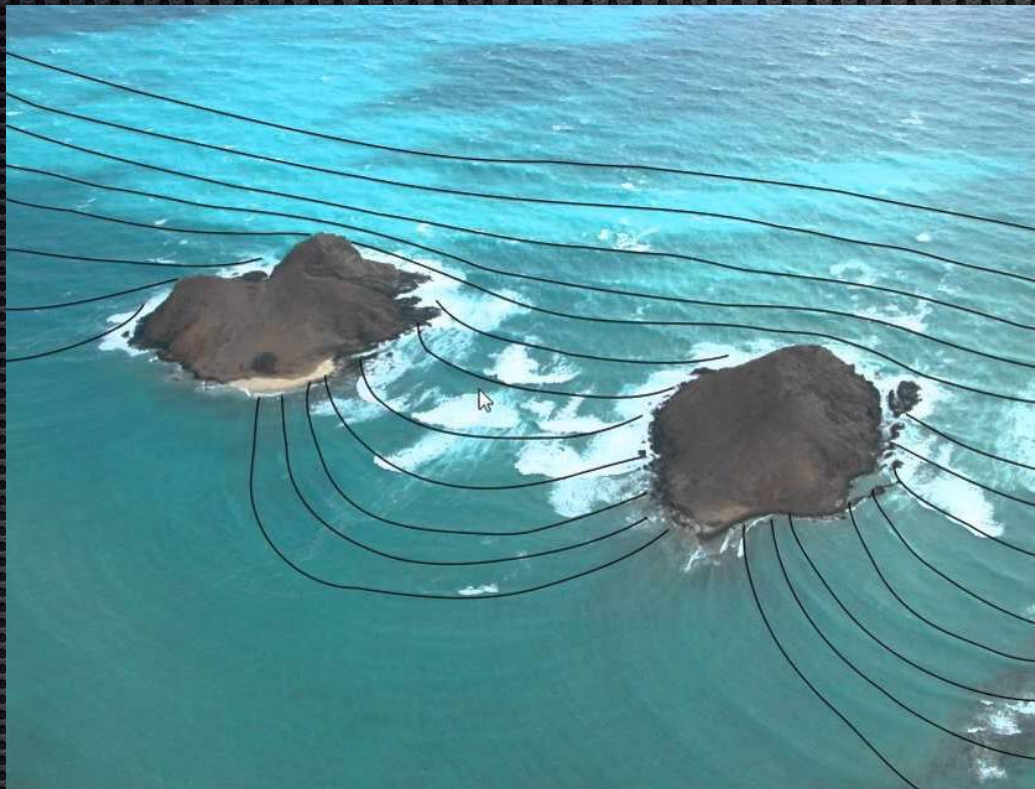
Cavità laser

La rifrazione



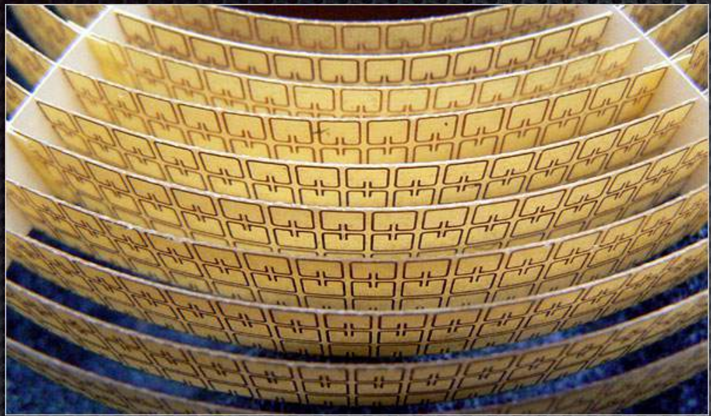
La velocità della luce cambia nel materiale (indice di rifrazione): cambia la lunghezza d’onda

La rifrazione

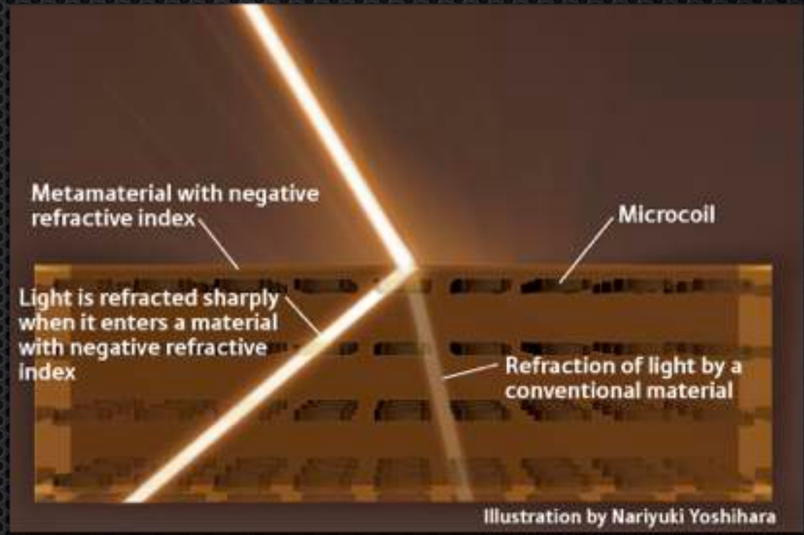


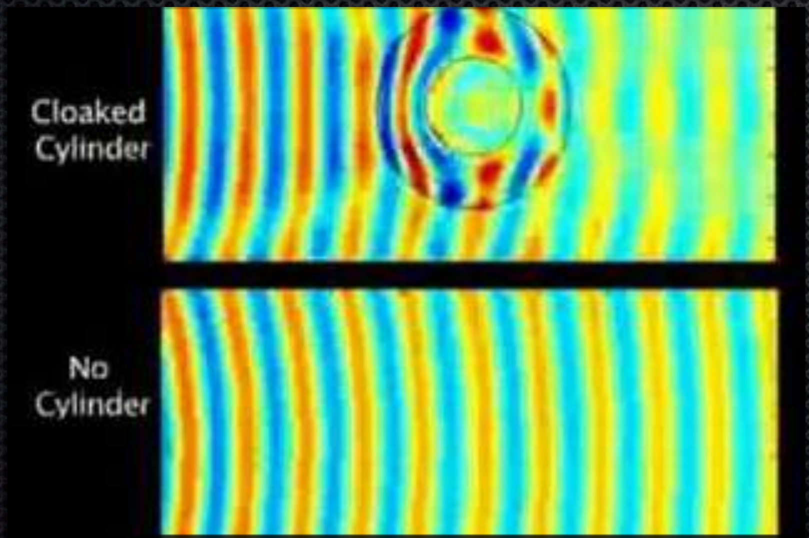
La velocità della luce cambia nel materiale (indice di rifrazione): cambia la lunghezza d'onda

Metamateriali (progetto n)



Rifrazione negativa

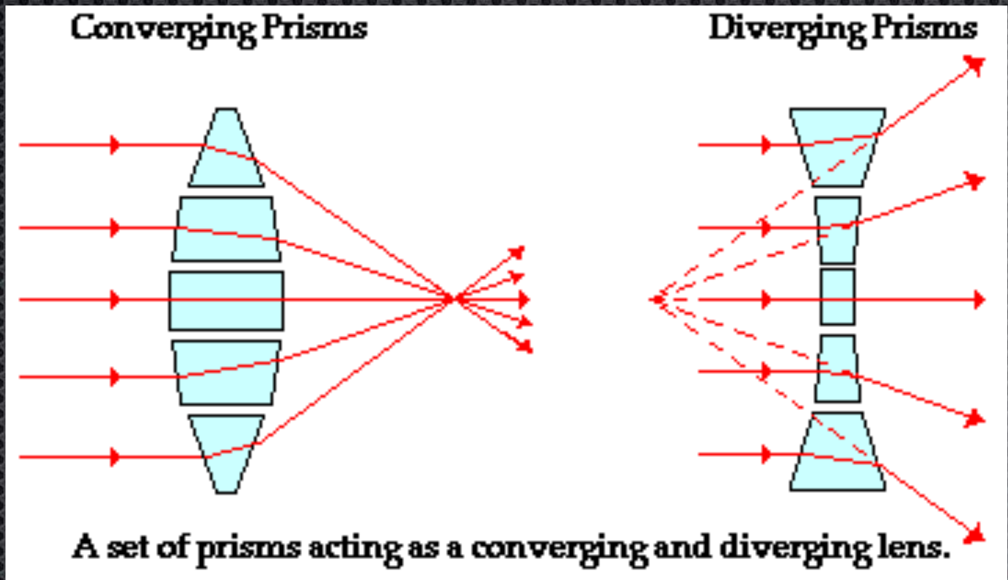




Mantello dell'invisibilità

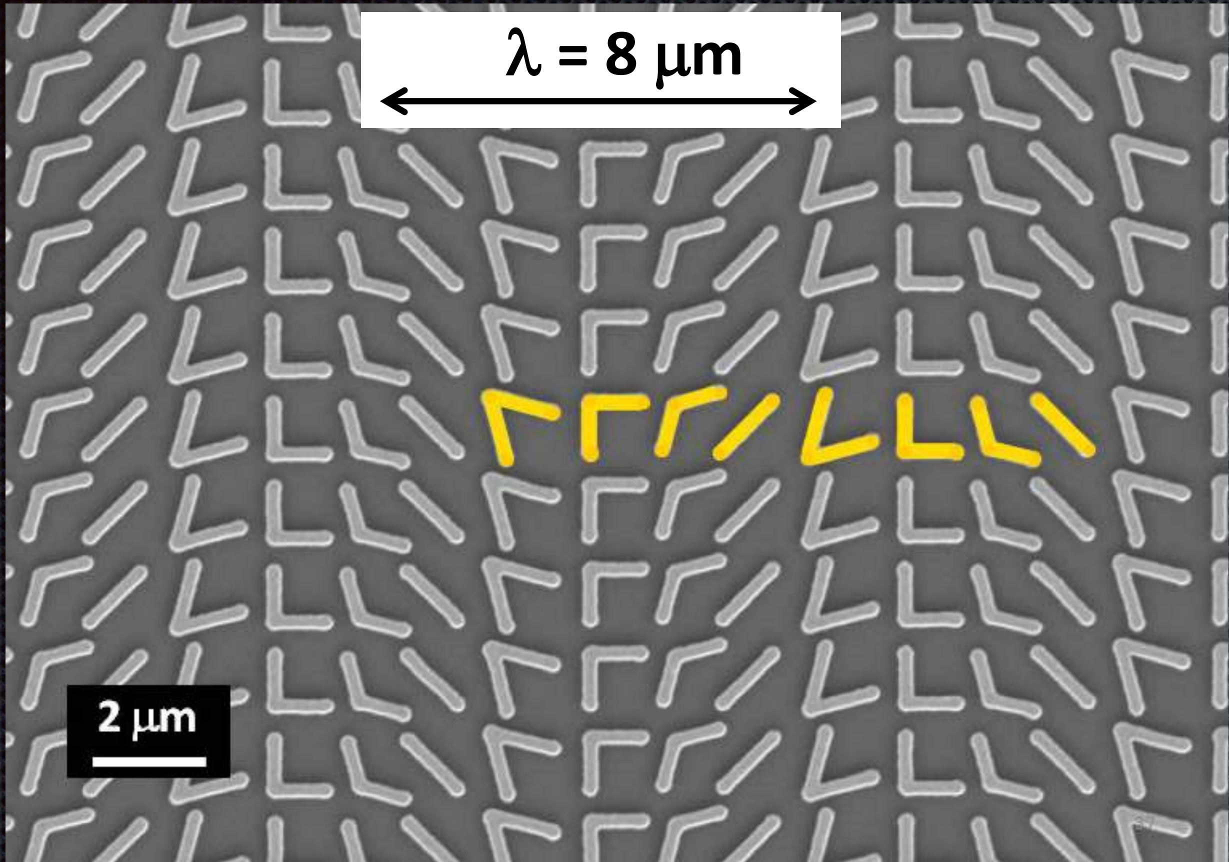
Lenti ?

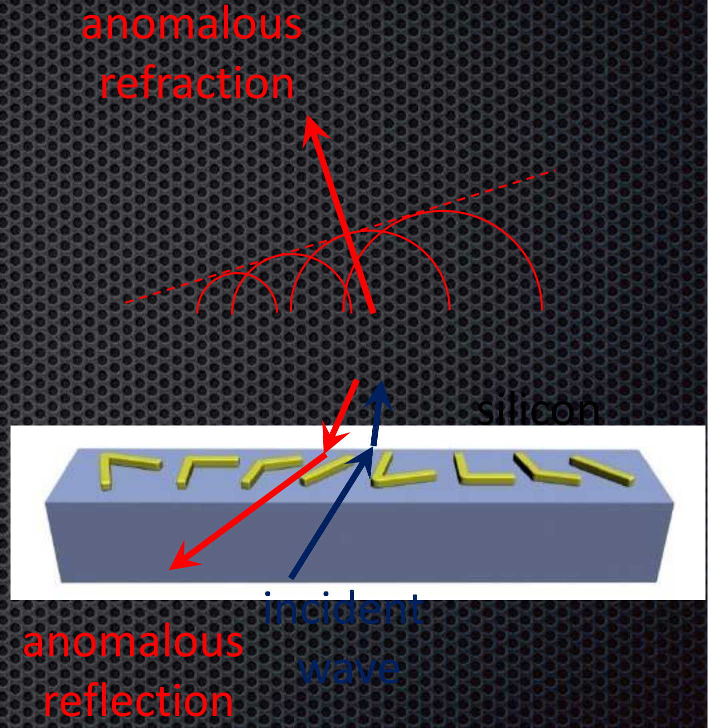
- Particolare forma delle lenti fa convergere o divergere i raggi luminosi

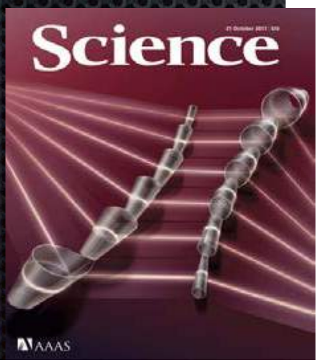


- Quanto sottili possono essere? Basta una superficie?

Metasuperfici







- ❑ Optically thin: 50nm
- ❑ Subwavelength phase resolution: ~λ/5
- ❑ Instant imprinting of a linear phase distribution
- ❑ Broadband (5-11 microns)

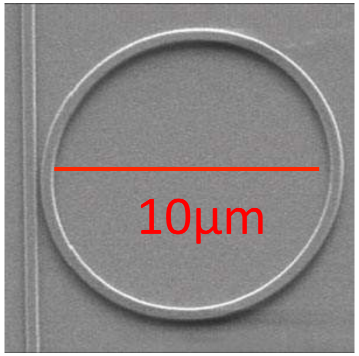
N. Yu *et al.*, *Science* **334**, 333 (2011)

Microcavities

need mechanism to trap light for long time

[llnl.gov]

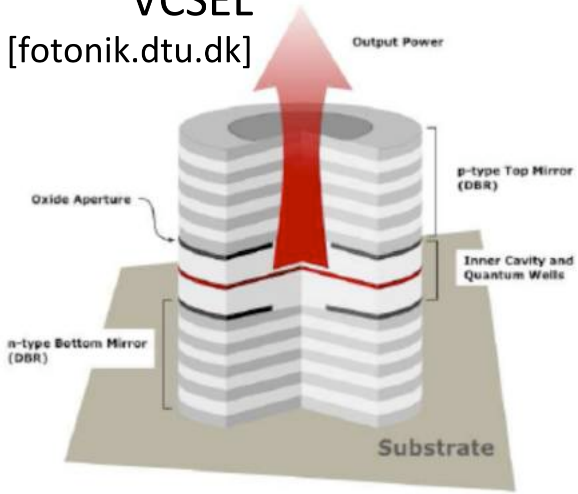
metallic cavities:
good for microwave,
dissipative for infrared

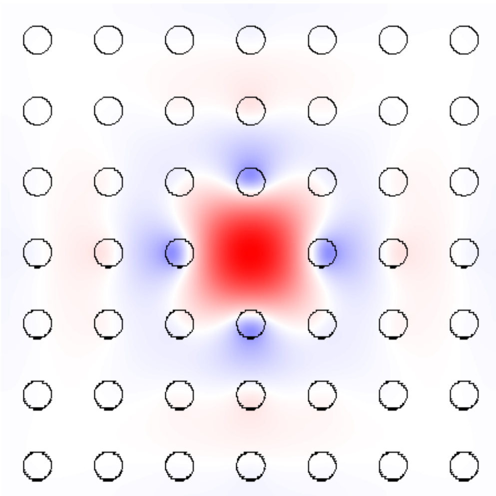


[Xu & Lipson (2005)]

ring/disc/sphere resonators:
a waveguide bent in circle,
bending loss ~ exp(–radius)

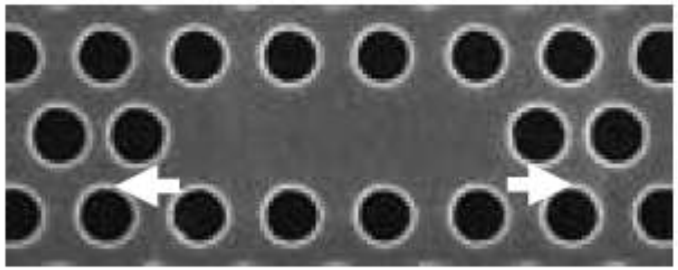
VCSEL
[fotonik.dtu.dk]





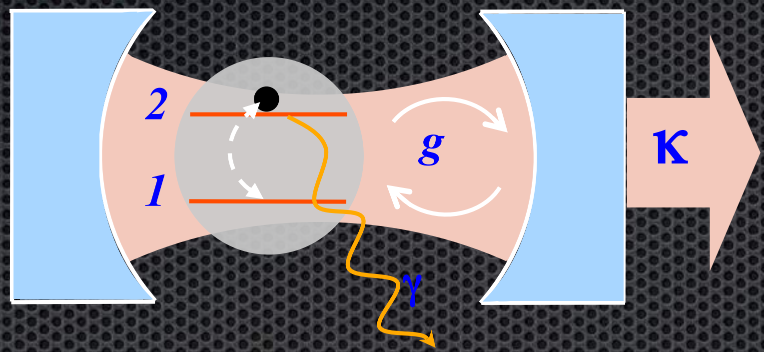
photonic bandgaps
(complete or partial
+ index-guiding)

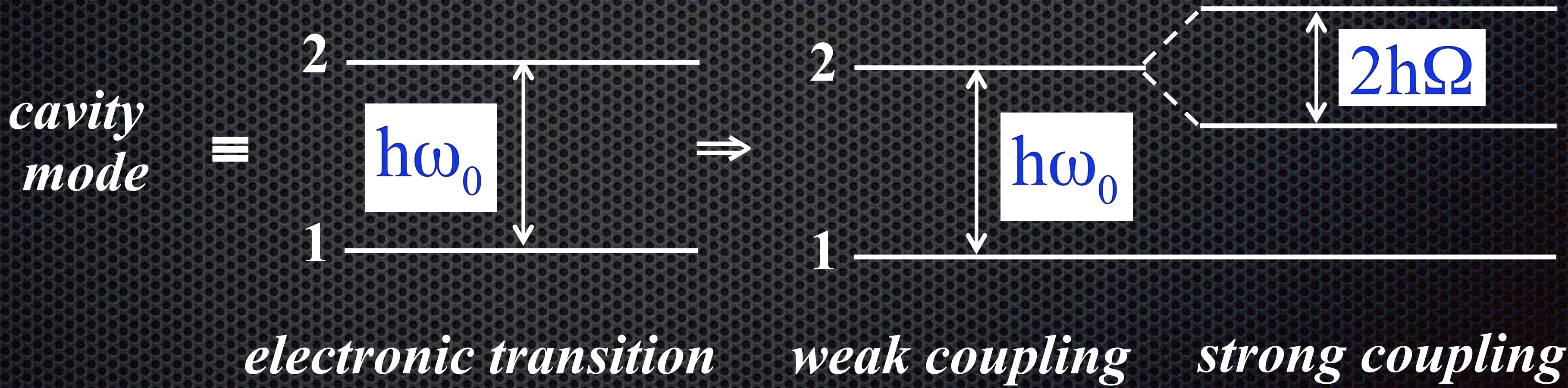
[Akahane, *Nature* **425**, 944 (2003)]



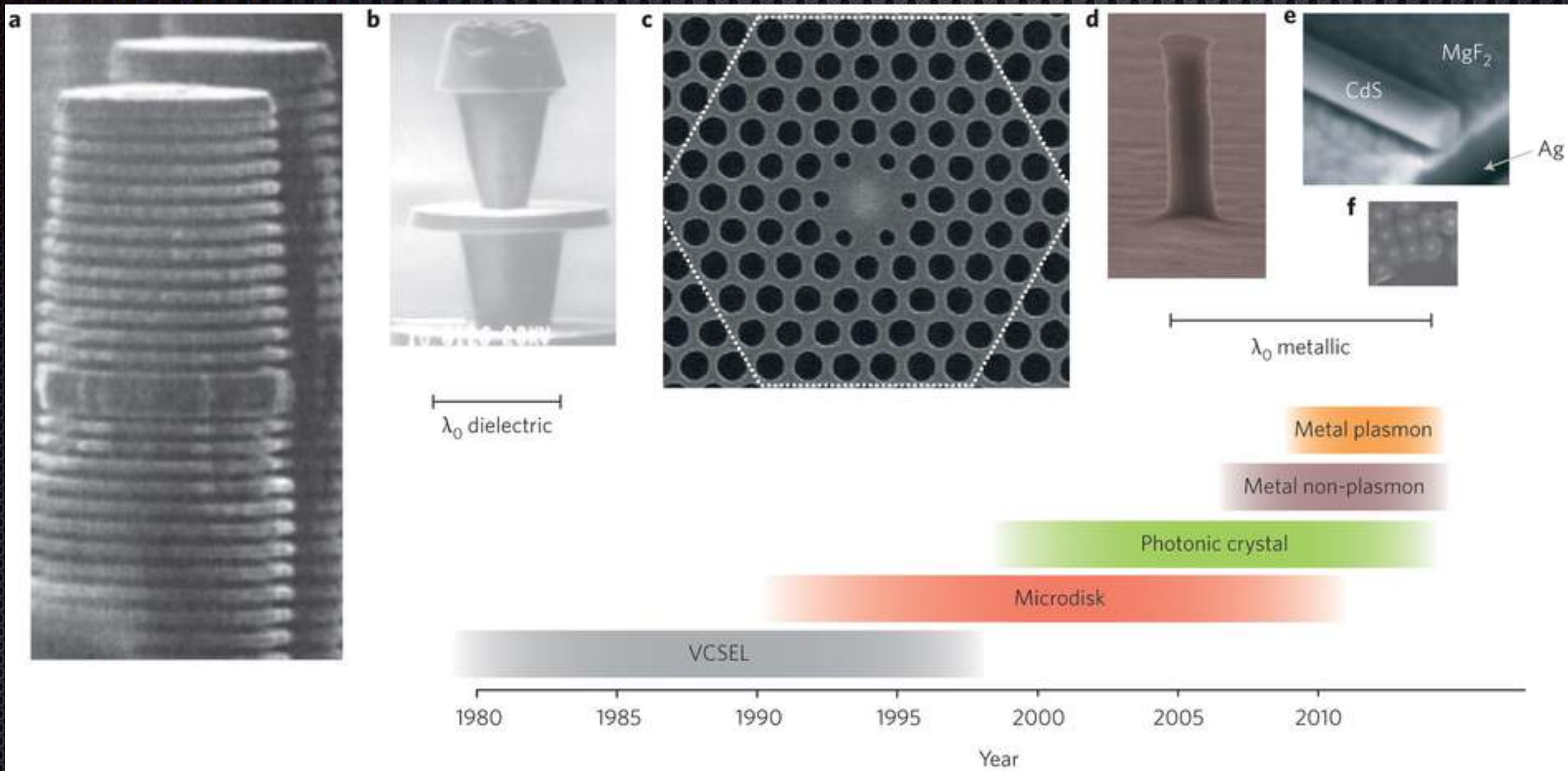
(planar Si slab)

Light-matter interaction





Weak coupling



High efficiency LEDs
Thresholdless lasers

Strong-coupling regime

Atomic physics: atoms in metallic microcavity

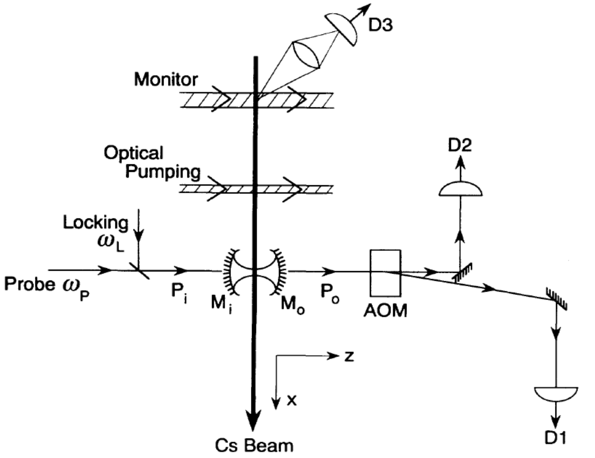
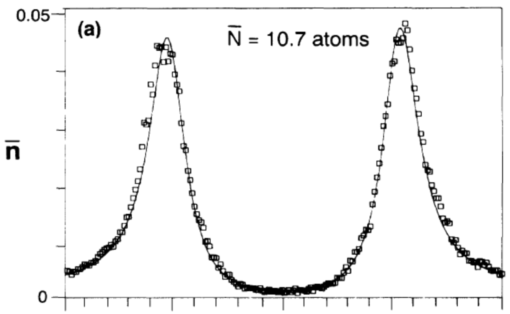


FIG. 1. Diagram of principal elements of the experiment.

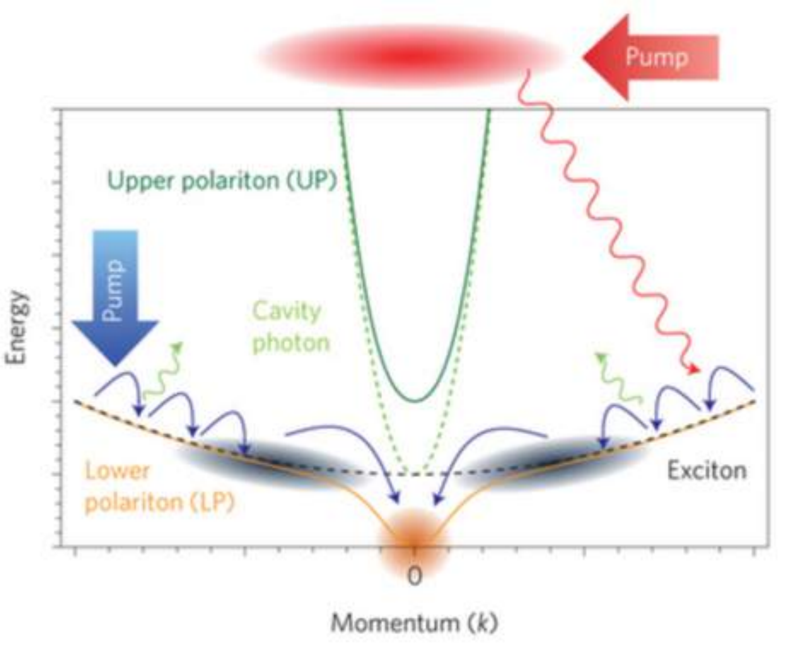


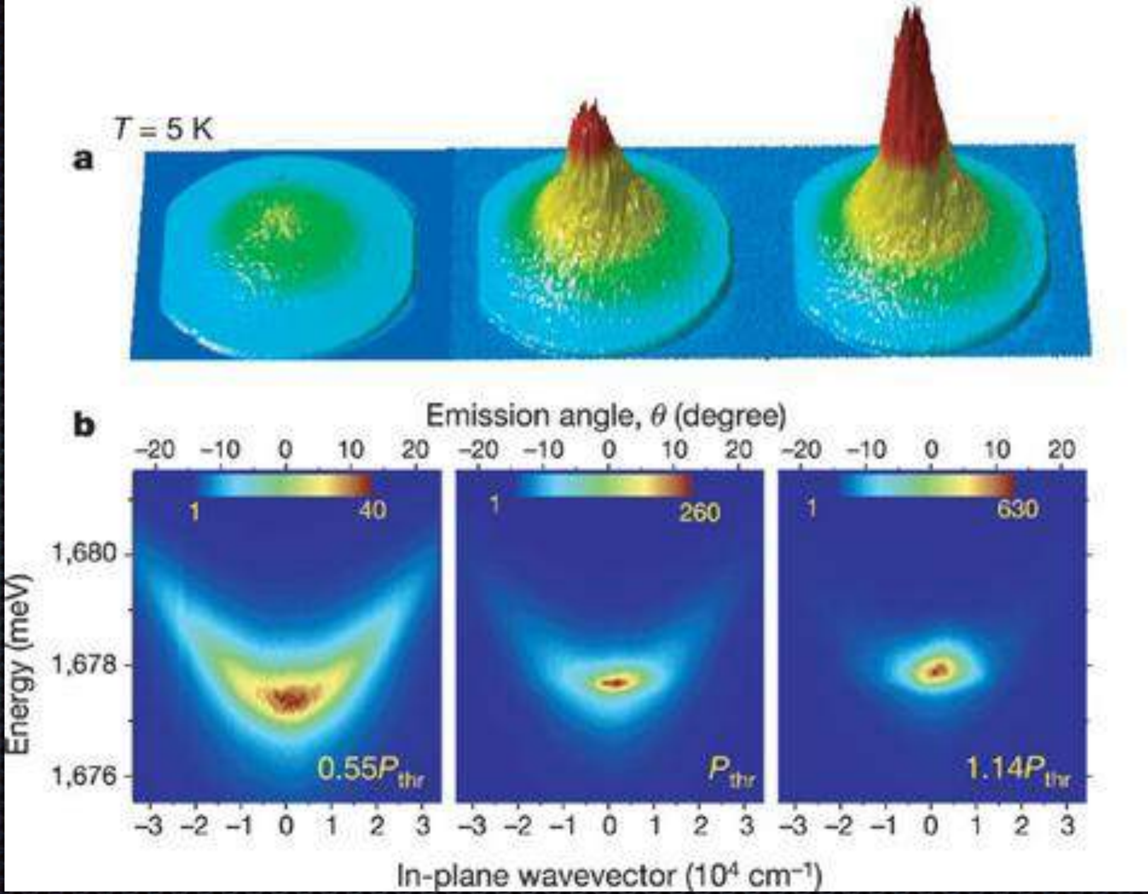
R. J. Thompson et al., PRL ***68****, 1132 (1992)*

Solid state physics:

- *excitons (bulk, QWs or QDs in semiconductor microcavities)*
- *qubits (cooper pair quantum-box in microwave resonators)*

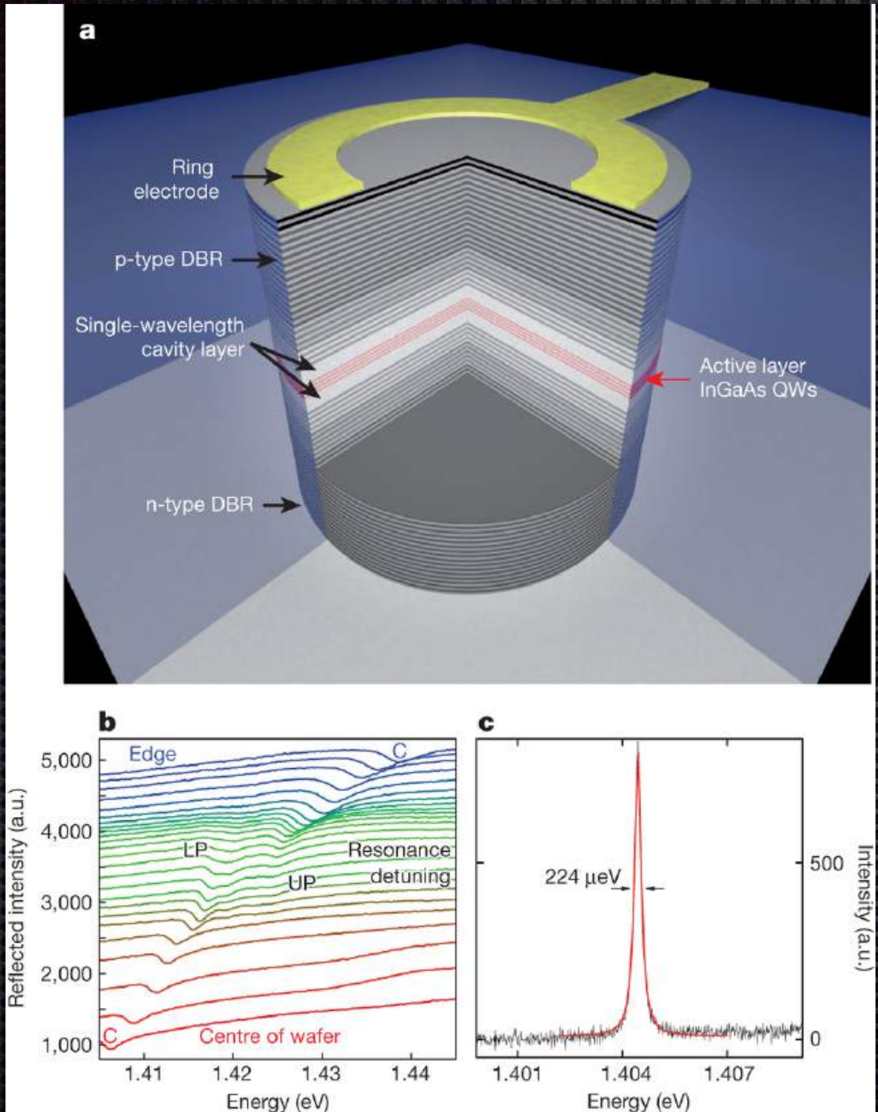
Polariton BEC





- Polaritons are bosons (almost)
- Non equilibrium
- Low effective mass
- Coherent light

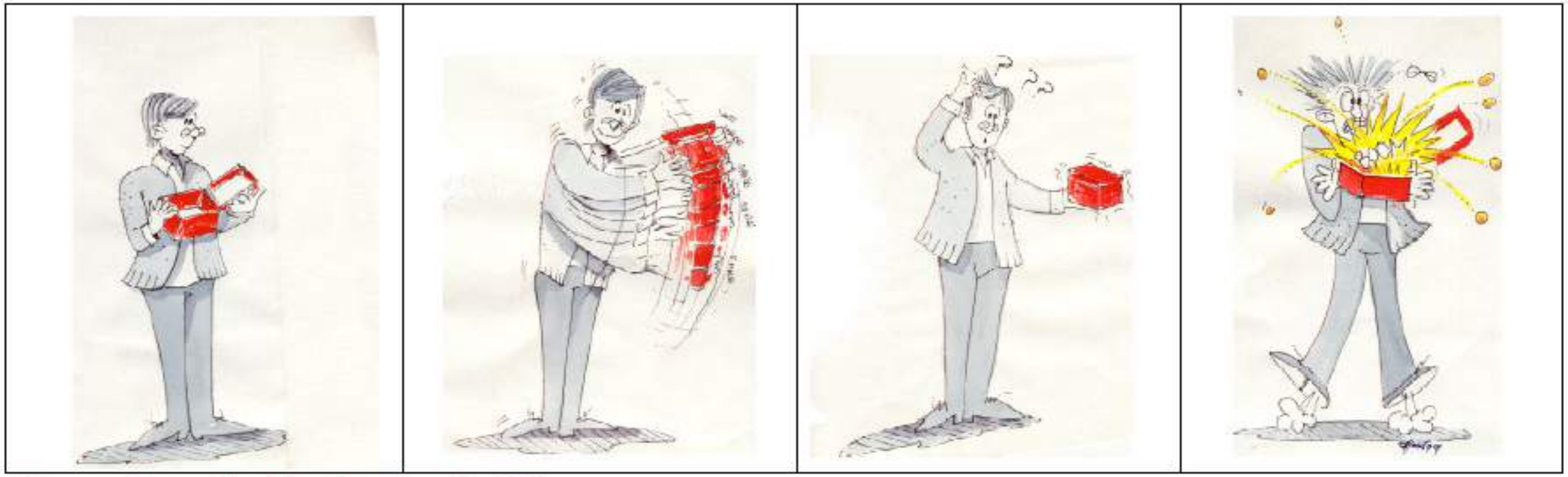
Polariton lasers



Final state stimulation:

polariton scattering on phonon bath is proportional to 1 + occupation number of final polariton state

Shaking the quantum vacuum ….

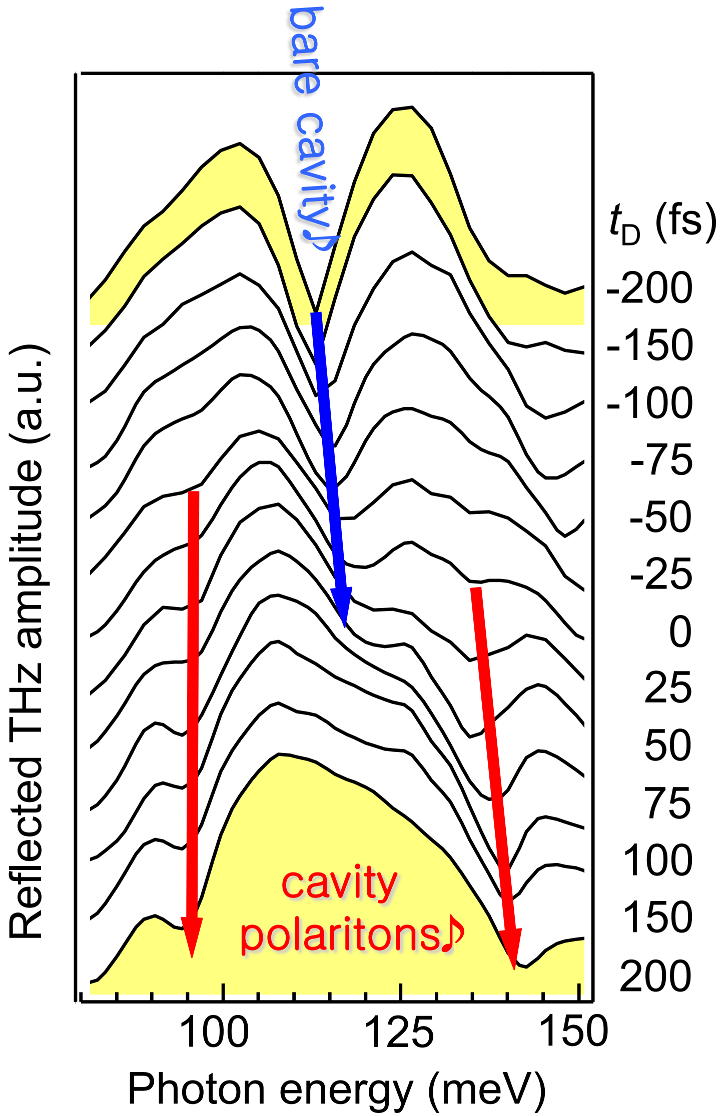


Giuseppe Ruoso - Les Houches - June 9, 2005

Getting photon pairs by modulating the quantum vacuum of a cavity system ….. The search for the dynamical Casimir effect

Non-adiabatic switching of ultrastrong coupling

T_L = 300 K

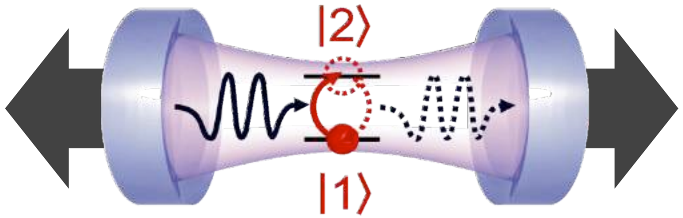


- Initially: bare cavity
- Control pulse induces ultrafast reflectivity changes of order 1
- **No gradual bifurcation** (compare to power tuning)
- Discontinuous, **non-adiabatic switching** from bare cavity to ultrastrongly coupled cavity polariton modes

G. Günter et al., Nature **458**, 178 (2009)

Perspectives

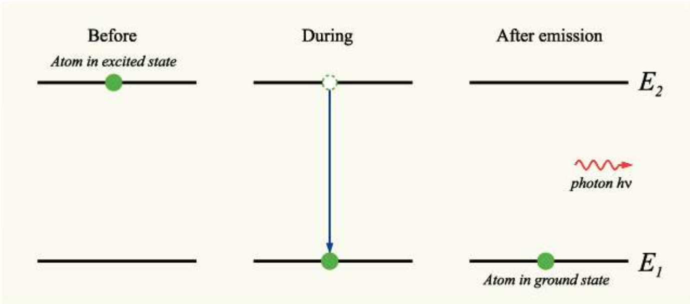
- **MIR-BOSE**



- release of correlated photon pairs out of the quantum vacuum?
- similar to **dynamical Casimir** effect and **Unruh-Hawking** radiation of black holes

- Ultrafast and scalable **room-temperature optical switching** and **mode-locked QCLs**

LED = emissione spontanea

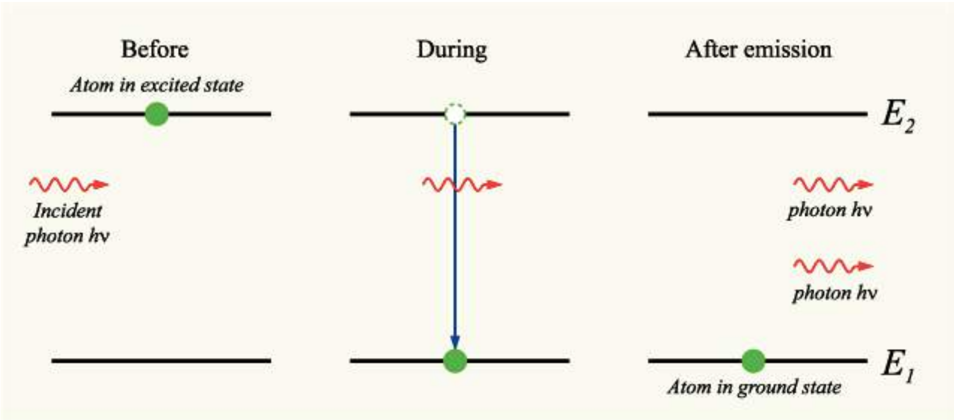


Braunstein: anni 50 prime misure dell'emissione spontanea in GaAs e altre leghe.

- Biard e Pittman: primi dispositivi elettroluminecenti in GaAs e brevetto (Texas Instruments) 1961
- Holonyak: 1962 primi LED visibili (General Electrics)

NATIONAL ENTERPRISE FOR NANOSCIENCE AND NANOTECHNOLOGY

Laser = emissione stimolata + cavità



Guadagno > perdite = autoscillazione

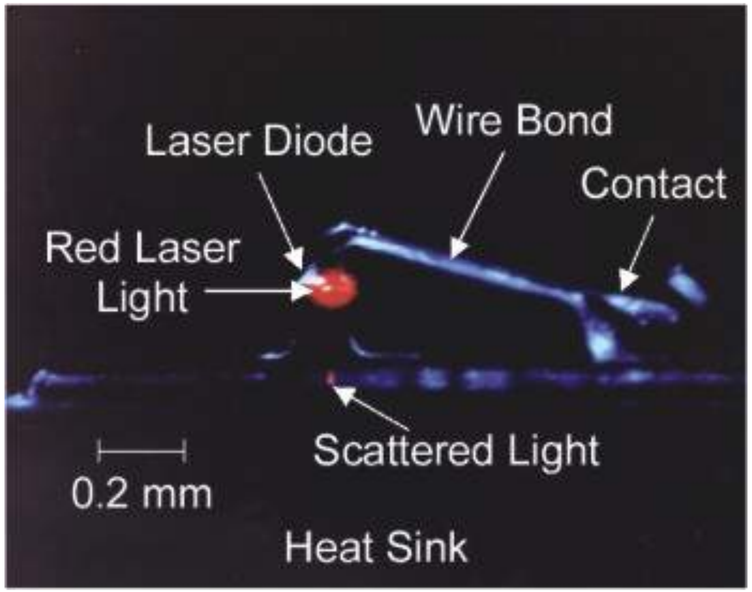
- Guadagno necessita inversione di popolazione per superare assorbimento
- Cavità serve per fornire feedback

Schawlow & Townes
Gould
Maiman 1960 Hughes Laboratories

NEST
National Enterprise for nanoScience and nanoTechnology

Laser a semiconduttore

Basov
Hall (1962) at General Electrics
and other teams (IBM, MIT)
Alferov (heterostructures)

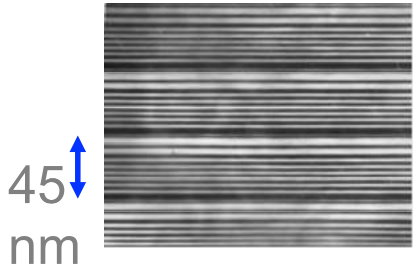


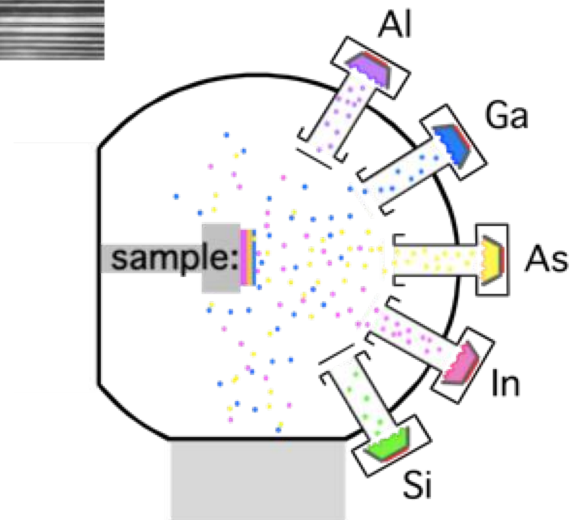
- Laser a semiconduttore
  - Iniezione elettronica
  - Monolitici
  - Miniaturizzabili
  - Integrabili

Telecomunicazioni
CD-ROM & players
Codici a barre
Armi intelligenti
….

Crescita epitassiale: MOCVD (anche MBE)

Molecular Beam Epitaxy (MBE)



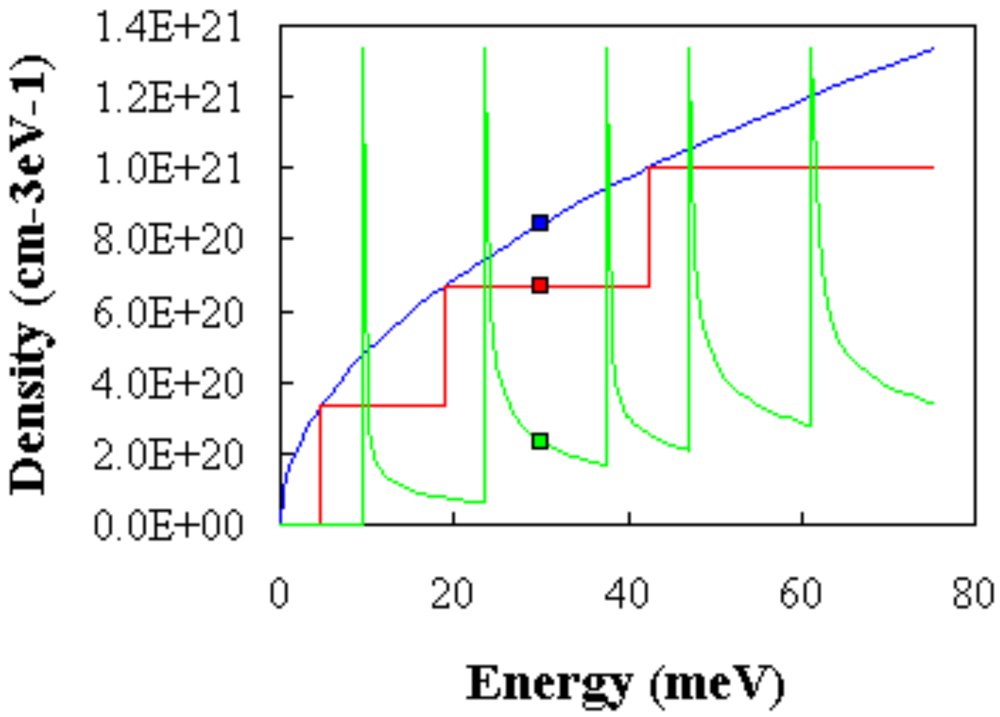


Cross-section of a few stages of QC-laser crystal crystal growth one atomic layer at a time

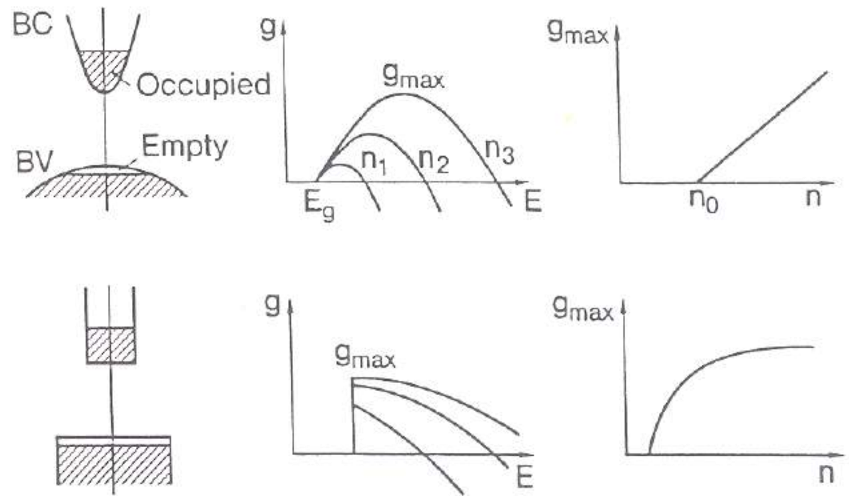
- Many (~ 500), few-atoms thick layers of alloy materials (Al, Ga, As, In);
- atomic control of layer thickness, 1 nanometer (nm) = 4 atomic layers
- atomically flat layer interfaces

NEST
National Enterprise for NanoScience and NanoTechnology

Dimensionalità



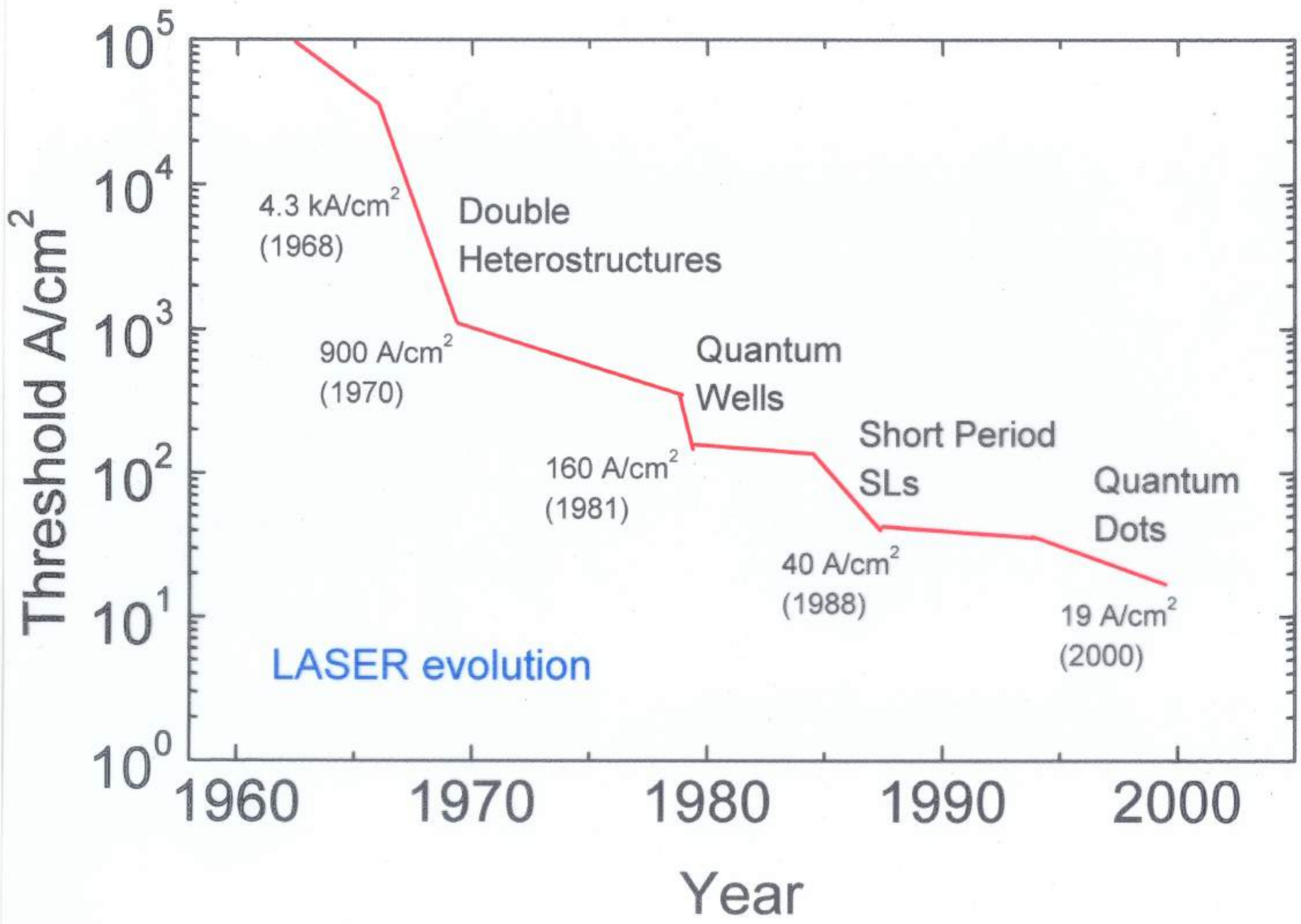
Inversione inizia dal gap



Più bassa è la dimensionalità, meno elettroni si sprecano, più alto è il guadagno

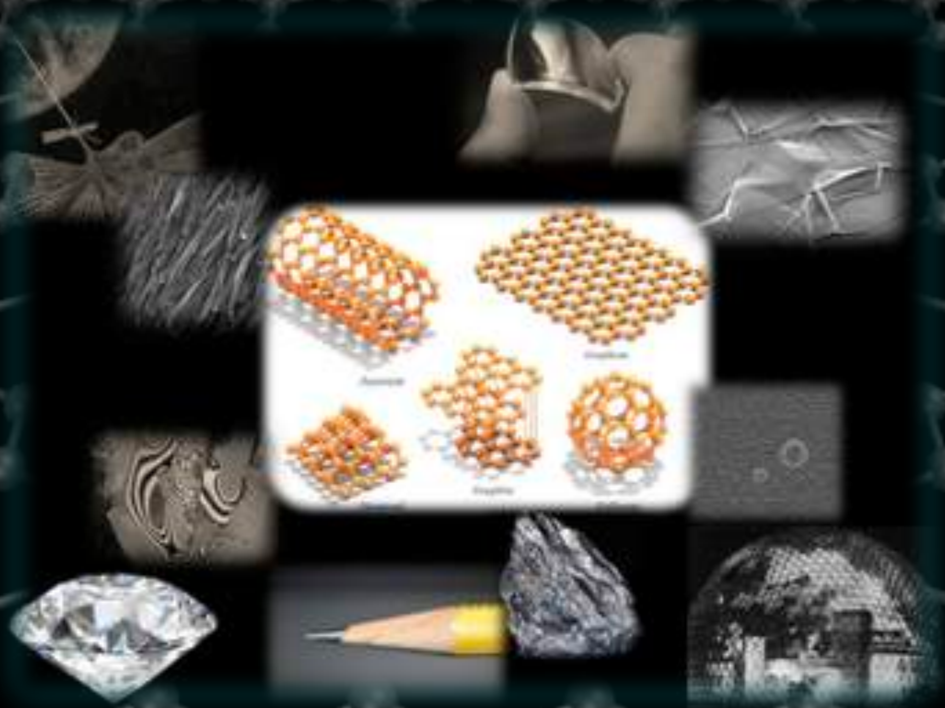
NATIONAL ENTERPRISE FOR NANOSCIENCE AND NANOTECHNOLOGY

Evoluzione dei laser a semiconduttore



NATIONAL ENTERPRISE FOR NANOSCIENCE AND NANOTECHNOLOGY

Graphene

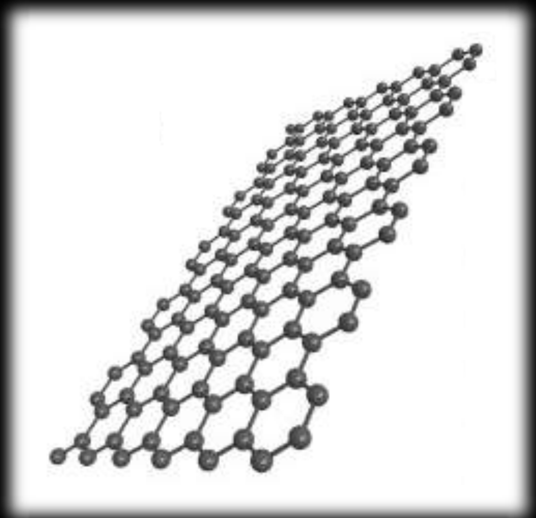


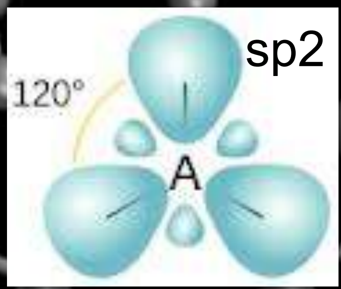
1 billion euro EC project

Grafene: esotico e comune

2004 **Andre Geim e Konstantin Novoselov** isolano e osservano il grafene

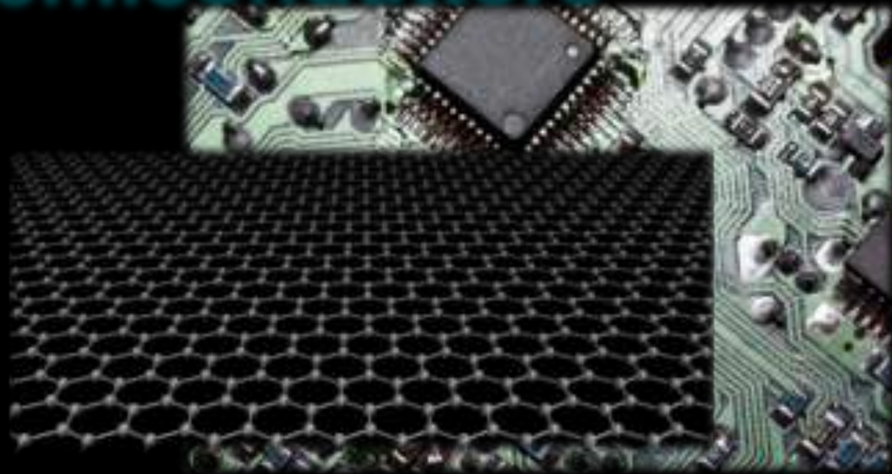
2010 **Nobel per la Fisica**
“... for groundbreaking experiments regarding the two-dimensional material **graphene”**





Grafene: conduttore e semiconduttore

Elettronica “grafenica”



- più veloce
- meno dissipativa
- più miniaturizzata

di quella tradizionale basata sul silicio...

... ma soprattutto con caratteristiche uniche...

Grafene ed energia

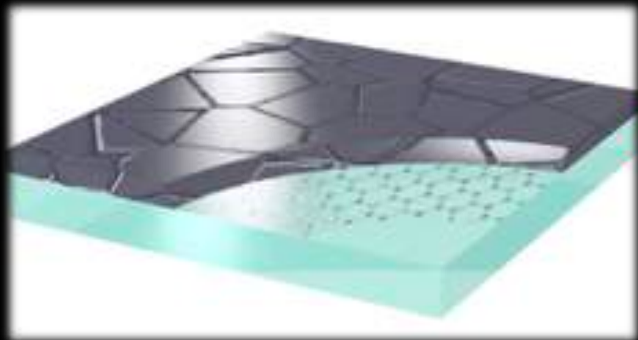
resistenza e flessibilità
elettronica veloce
integrabilità e miniaturizzazione

leggerezza
trasparenza

→ vasta superficie accessibile per unità di massa

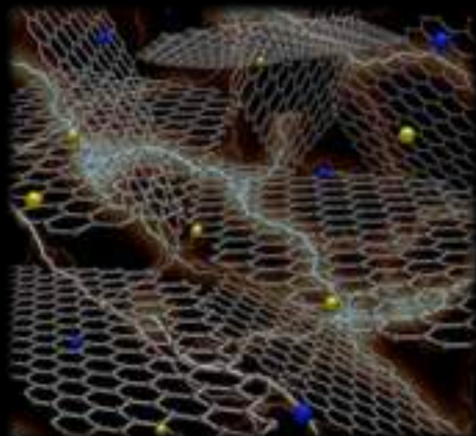
Nella produzione di energia: fotovoltaico

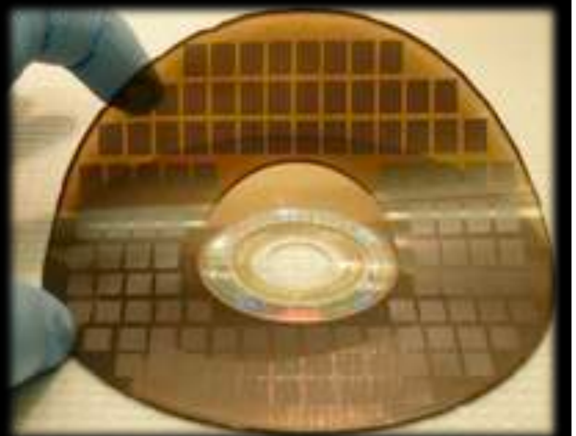
dispositivi flessibili (indossabili)
economici
efficienti



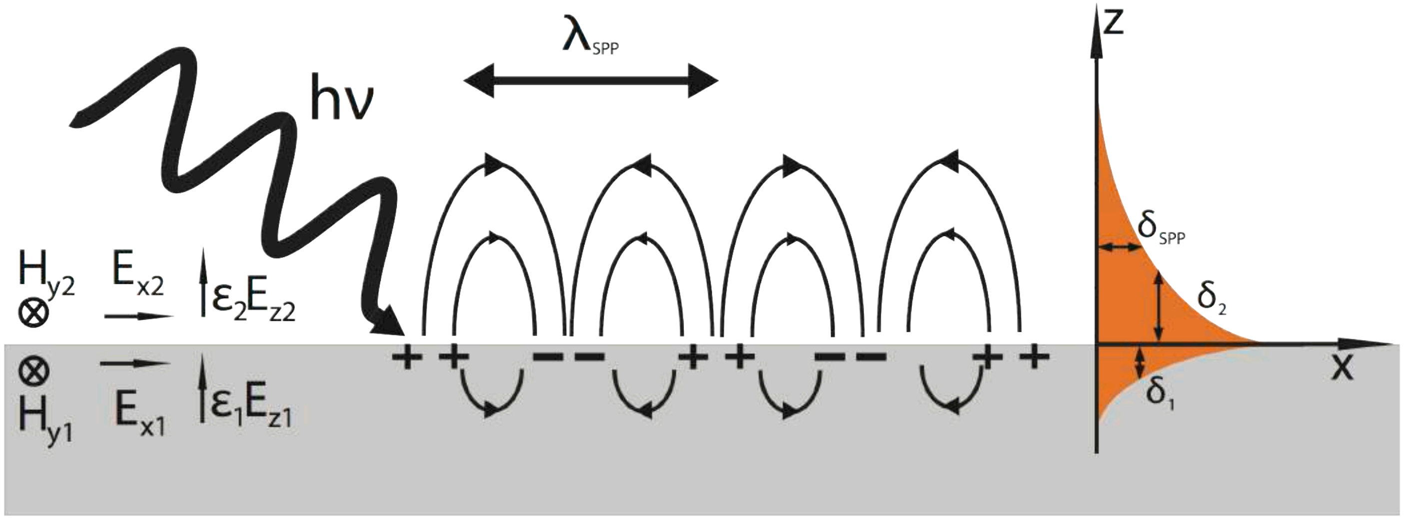
Nell'immagazzinamento di energia:

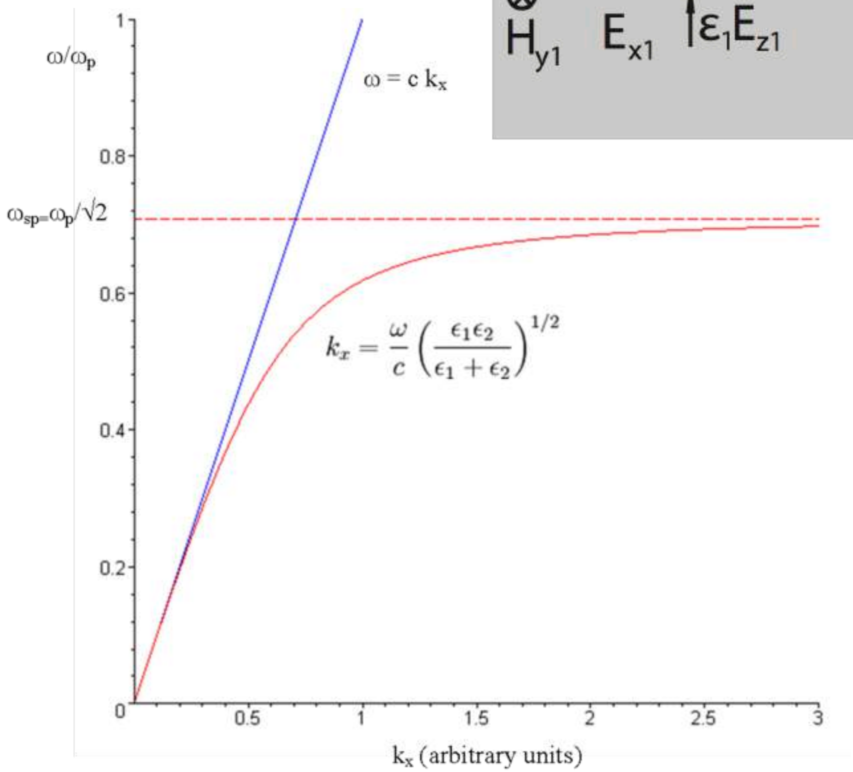
Super batterie e super condensatori ad alta efficienza, trasportabili veloci ed economici





Surface plasmons



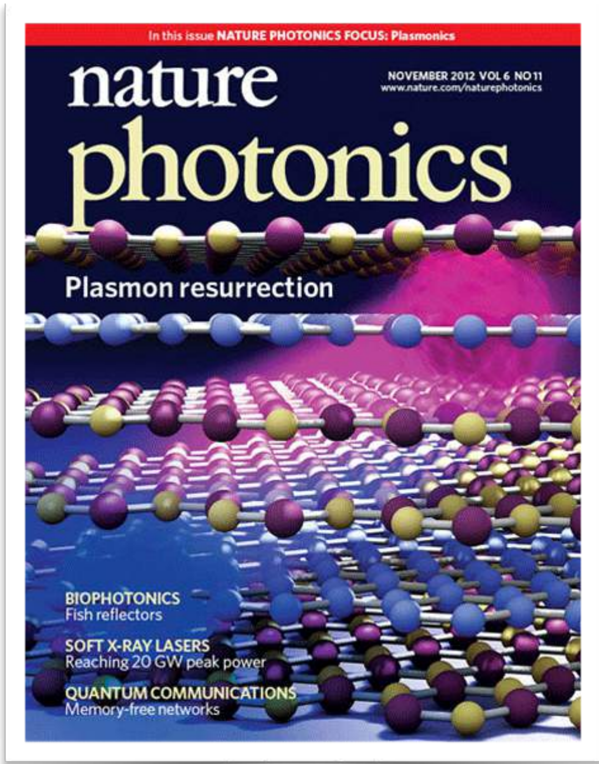


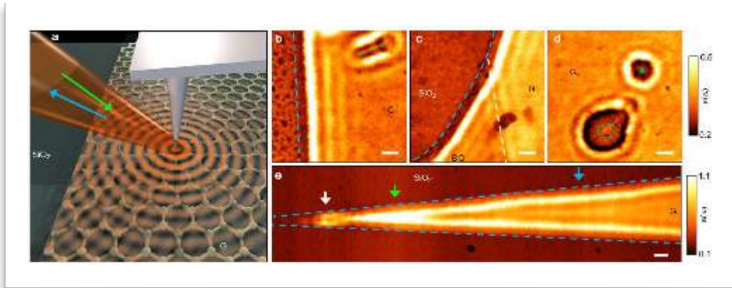
"Good" metal:
low confinement, low loss

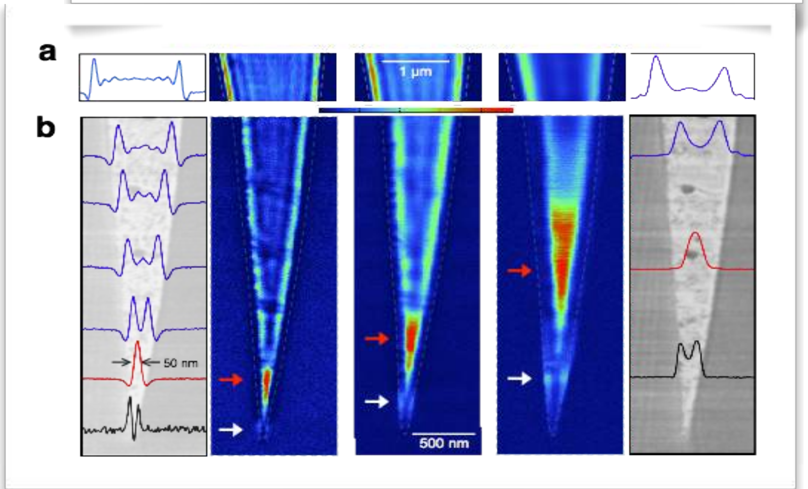
"Bad" metal:
high confinement, high loss

Graphene plasmonics?

- Exceptional plasmonic material





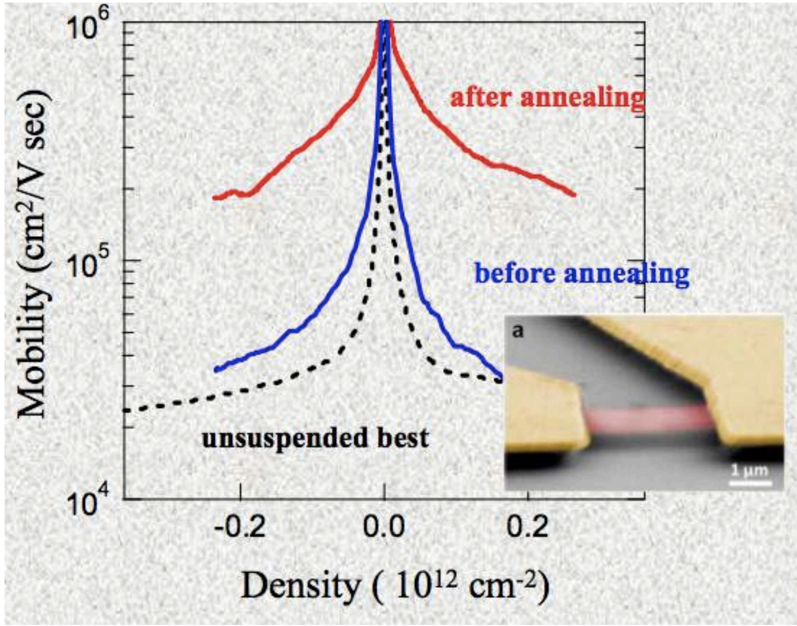


Low propagation losses

High field localization

Why graphene?

- Excellent semiconductor / conductor

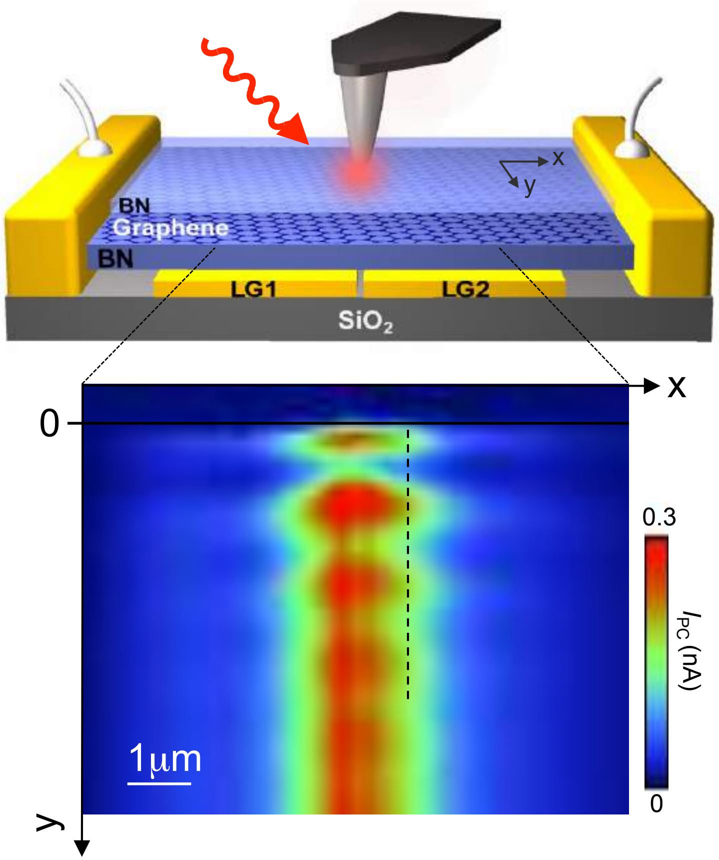


Ultra high mobilities

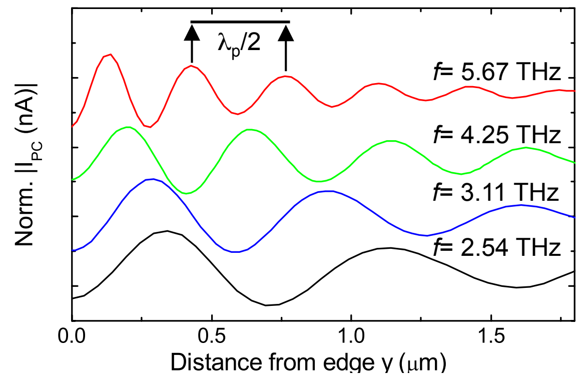
Gate tunable carrier density can be switched from holes to electrons

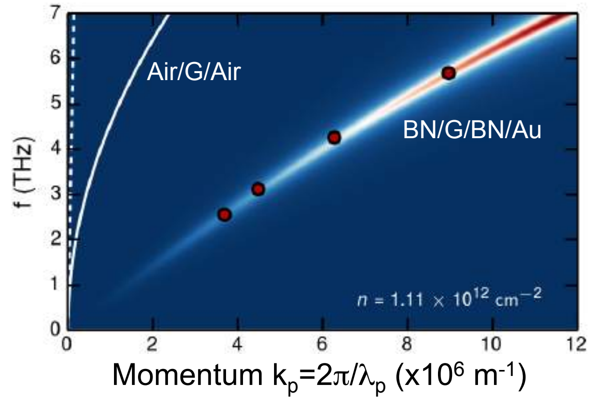
THz photocurrent nanoscopy
for mapping plasmons in THz photodetector

Near-field photocurrent nanoscopy developed at nanoGUNE and ICFO allows for mapping THz graphene plasmons in (split) gated devices.



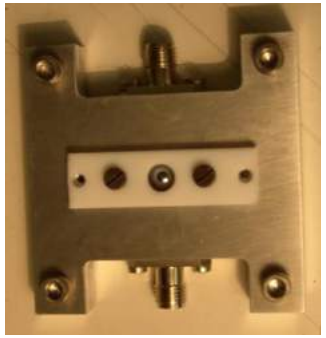
Near-field photocurrent image shows fringes revealing the excitation of plasmons.

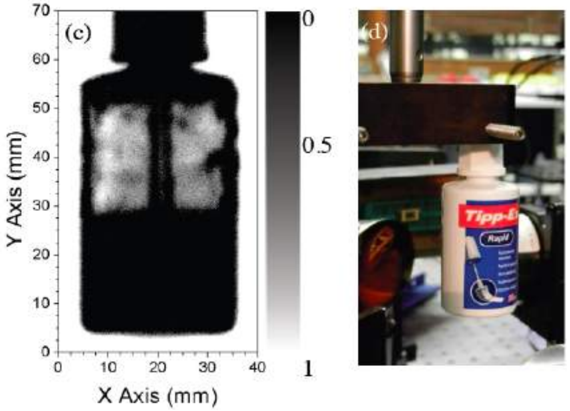




The fringe spacing as a function of incident frequency matches the simulated dispersion of THz graphene plasmons.

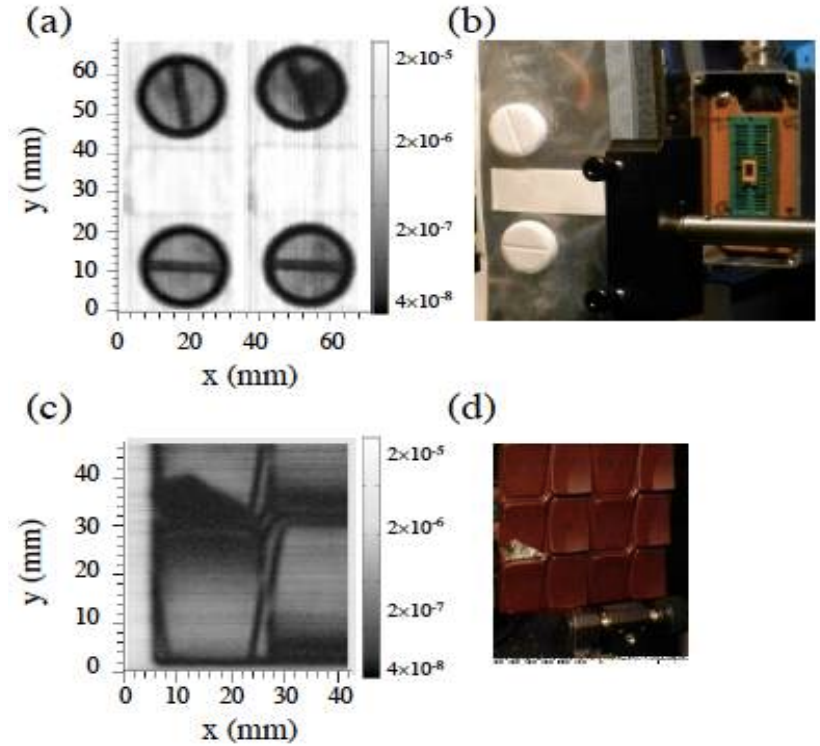
THz Imaging





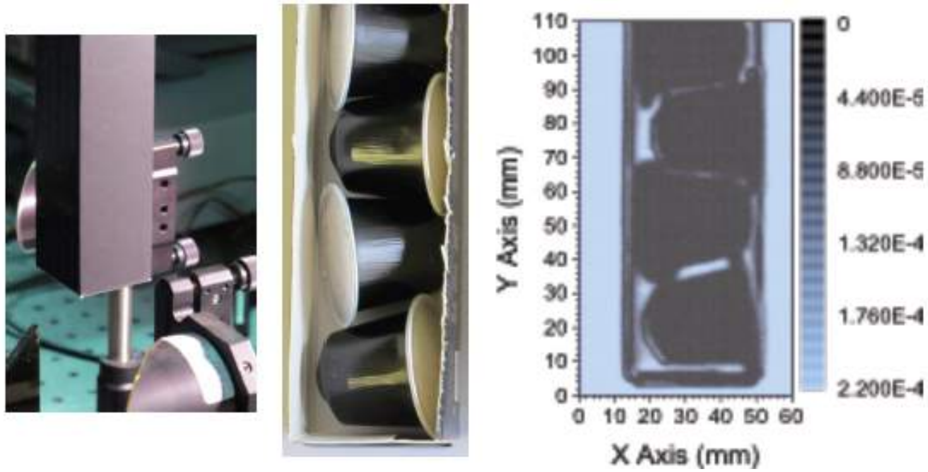
$Bi_2Te_{2.2}Se_{0.8}$ Surface states

Phosphorene



200 x 550 scanned points,
integration time of 20 ms/point

Graphene



L. Vicarelli, et al, **Nature Materials** (2012)

400 x 700 Pixel Imaging