Scuola di Dottorato in Ingegneria Leonardo da Vinci – a.a. 2012/13

LASER: CARATTERISTICHE, PRINCIPI FISICI, APPLICAZIONI

(MICROSCOPIA E NANOSCOPIA)

Versione 4 – Giugno 2013 – http://www.df.unipi.it/~fuso/dida

Part 1
Introductory remarks:
what, when, how (and why)

GENERAL INFO

The course has three main themes:

1. To recall and review the main basic mechanisms ruling the operation of a laser:
   - Light/matter interaction in classical terms;
   - A few concepts of quantum mechanics (QM) and the semiclassical approach;
   - Processes which can be explained only by using QM

2. To briefly review different types of laser systems and their main features:
   - Pumping methods (optical, electronics);
   - Optical cavities;
   - Specific applications for specific laser systems

3. To discuss applications where the properties of laser light play a crucial role:
   - Metrology, microscopy, nanoscopy;
   - Other applications of interest to you (to be decided with you!)

Practical info: foreseen duration 20-24 hours (3* cfu)
Final test: short written test + (possibly) a very short presentation
More and duly updated info on: http://www.df.unipi.it/~fuso/dida

*or more, depending on the PhD class

OUTLOOK OF THIS LECTURE

- **What** a laser is:
  the main astonishing features of a laser and their common understanding

- **When** the laser has been conceived:
  some historical remarks and the growth of applications

- **Why** the laser is so unique (first steps to the answer):
  what makes the laser light so attractive and useful

- **How** to describe light, matter and their interaction:
  just a few anticipations of what will be more widely treated in the next lectures

(*Unfortunately*) the topic requires a few quantum mechanics (QM)

⇩

The needed QM concepts will be briefly introduced in the next lectures

NOMINA SUNT IN REBUS

Light and Radiation are obviously involved in lasers

L. : light
A.: amplifier
S.: stimulated
E.: emission
R.: radiation

Stimulated emission (what is that?) is a key ingredient

(this requires QM to be understood)

Careful, however! Laser is an oscillator, rather than an amplifier
(nonetheless, amplification of light obtained with stimulated emission processes is another ket ingredient)

LASERs derive from MASERs (M stands for Microwave, at present masers are no longer investigated, at least they are investigated and used much less than lasers)

- 10^9 yr. B.C. First lasers were OH molecules, 1.6 GHz, in the cosmos, invented by mother nature. They were "masers": *Microwave Amplification by Stimulated Emission of Radiation*.
- 1954: First manmade maser, Townes Gordon Zeiger, 24 GHz ammonia (NH_4)

HISTORICAL REMARKS

17: EINSTEIN formula la teoria dell'emissione stimolata per spiegare la legge di corpo nero di Planck
39: V.Fabrikant (URSS) prevede l'uso dell'emissione stimolata per amplificare onde "corte
50: messa a punto del pomappgio ottico (inversione di popolazione grazie all'energia luminosa) da parte di A.KASTLER e J.BROSSEL
51: C.TOWNES (USA) N.BASOV, A.PROKHROV (URSS) teoria dell'emissione stimolata per l'amplificazione
54: GORDON mette a punto il MASER (Microwave Amplification by Stimulated Emission of Radiation)
58: TOWNES e A.SCHAWLOW, e BASOV, indicano che il principio del MASER può esser applicato alla luce
60: BASOV, O.KROKHIN e Yu.POPOV sviluppano la teoria del laser
60: primo laser a rubino realizzato da T.MAIMAN negli USA
61: primo laser a gas sviluppato da A.JAVAN, W.BENNET e D.HERRIOT (He-Ne). E' il las più usato nel mondo
63: messa a punto del laser ad anidride carbonica da parte di C.PATEL
63: Premio Nobel in Fisica per l'invenzione del laser a BASOV, TOWNES e PROKHROV
69: funzionamento a temperatura ambiente dei laser a semiconduttori (diodi laser)

SCIENCE AND TECHNOLOGY

Since the first invention, lasers have been greatly developed and diffusion of lasers is now exceptionally wide (maybe, comparable or even more than mobile phones)

Development has been driven by technological refinements (no, or very few, major revolutions) and, quite often, by the quest for new applications

However, not all promises have been satisfied (e.g., laser sources at any wavelength, use of laser for mass applications like lighting,…) and in some cases quality has not advanced alot (see, e.g., the diode laser)

Anyway, at the beginning laser was claimed to be
"***A solution without a problem***"

But now it appears as
"***The solution for many problems***"
(both basics and applicative)

LASER AND FUNDAMENTAL RESEARCH

Strict and complex interplay between fundamental and applicative research issues
For instance, let's have a look at the list of Nobel Prizes in Physics (last ~15 yrs)

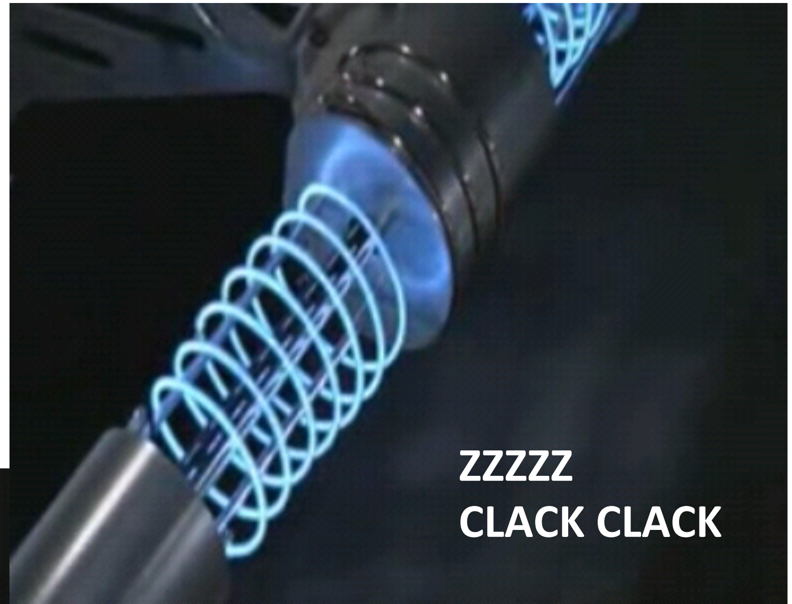
- 2010
  Andre Geim, Konstantin Novoselov ← *(Identification of graphene by laser (Raman) spectroscopy)*
- 2009
  Charles Kuen Kao, Willard S. Boyle, George E. Smith ← *Photonics and TLC*
- 2008
  Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa
- 2007
  Albert Fert, Peter Grünberg
- 2006
  John C. Mather, George F. Smoot
- 2005
  Roy J. Glauber, John L. Hall, Theodor W. Hänsch ← *Quantum optics and laser combs*
- 2004
  David J. Gross, H. David Politzer, Frank Wilczek
- 2003
  Alexei A. Abrikosov, Vitaly L. Ginzburg, Anthony J. Leggett
- 2002
  Raymond Davis Jr., Masatoshi Koshiba, Riccardo Giacconi
- 2001
  Eric A. Cornell, Wolfgang Ketterle, Carl E. Wieman ← *Laser manipulation of the matter and BEC*
- 2000
  Zhores I. Alferov, Herbert Kroemer, Jack S. Kilby ← *Etherostructures and diode laser*
- 1999
  Gerardus 't Hooft, Martinus J.G. Veltman
- 1998
  Robert B. Laughlin, Horst L. Störmer, Daniel C. Tsui
- 1997
  Steven Chu, Claude Cohen-Tannoudji, William D. Phillips ← *Laser cooling*

The Nobel Prize in Physics 2012
Serge Haroche and David J. Wineland
"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

← *Laser spectroscopy and manipulation of single atoms*

The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt and Adam G. Riess
"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

MY OWN FIRST GENERAL UNDERSTANDING OF LASER



Goldfinger 1962

“Power” (e.g., power to cut a thick steel plate) is indeed one of the main concepts coming to the mind when speaking of lasers

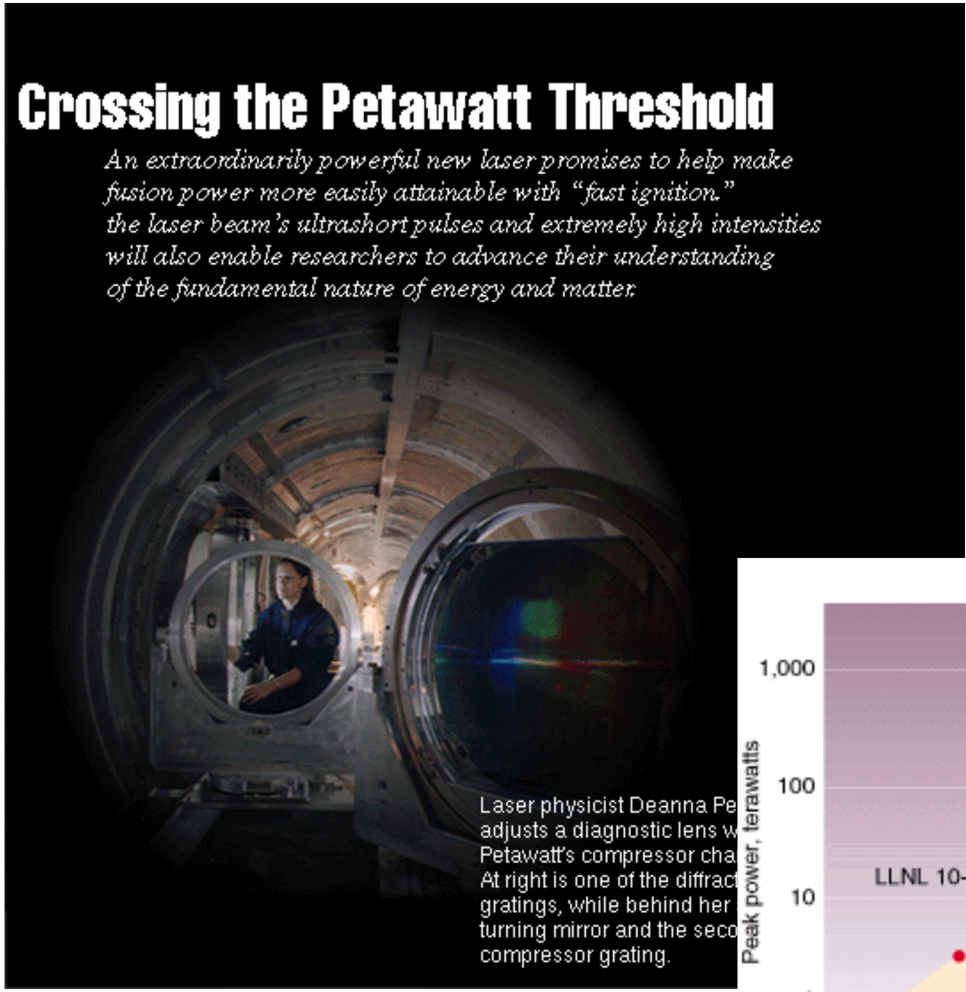
NO COMMENT

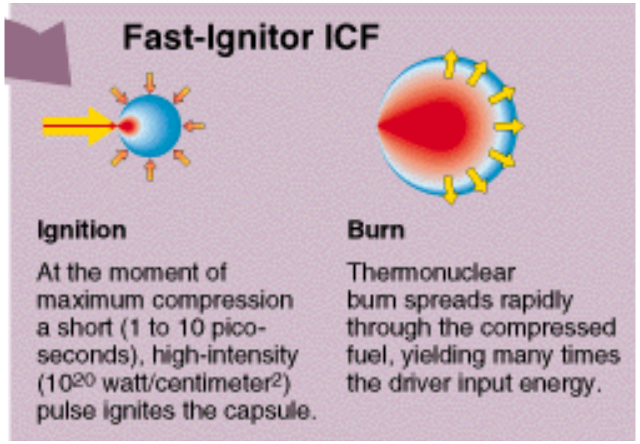
Death rays, laser swords, stellar lasers, have been mentioned in the society and in the fiction for many years…

Star Wars: quelle vere di Bush

I satelliti Usa saranno armati e in grado di colpire qualunque luogo terrestre
Questo progetto metterebbe nuovamente in pericolo gli equilibri internazionali

THE PETAWATT FRONTIER …





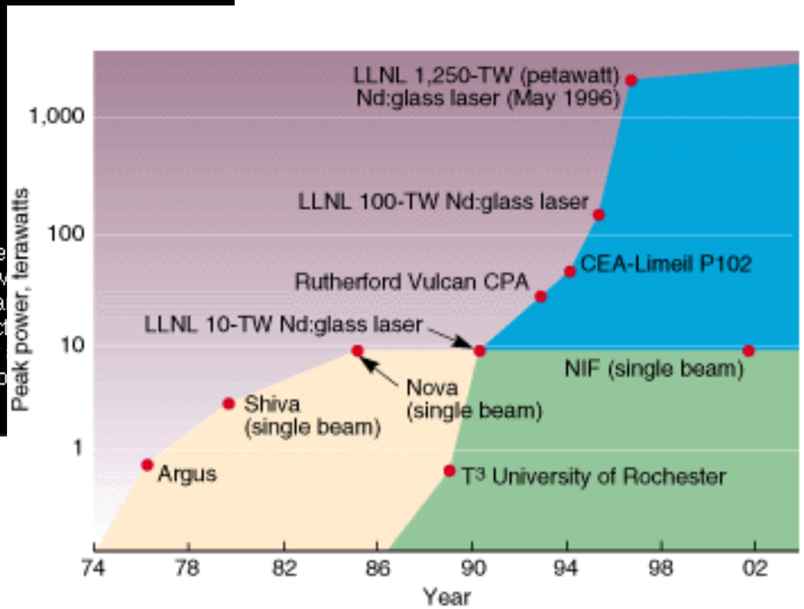


Figure 2. Milestones in laser development: early lasers (yellow), long-pulse technology (green), and chirped-pulse amplification technology (blue).

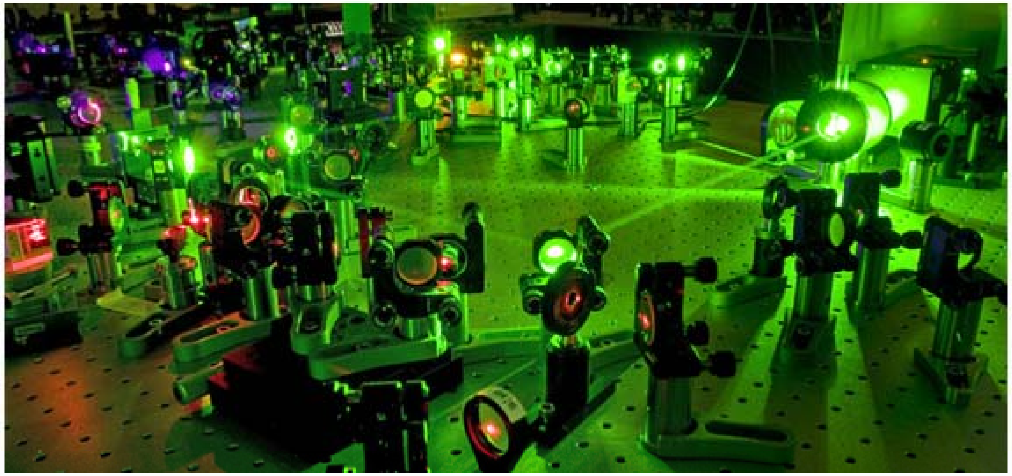
1 PW = 10^{18} W !!

… AND ABOVE

Powerful lasers needed for specific tasks
(in big collaborations)

The Vulcan 10 Petawatt Project

The project is to upgrade Vulcan to the 10 Petawatt (PW) power level (300J in 30fs) and provide focussed intensities of 10^{23} Wcm^{-2} to its user community. These unprecedented optical fields will open up a plethora of new scientific opportunities, which could enable tests of some of the most fundamental scientific theories. This upgrade will rely on a new technology, known as Optical Parametric Chirped Pulse Amplification or OPCPA that has been pioneered by the CLF.



Note: what is typically needed in many applications is a high intensity, i.e., **power** over irradiated **area**

Example:
100fs pulses with average power 1W
→ Peak power 10^{13}W

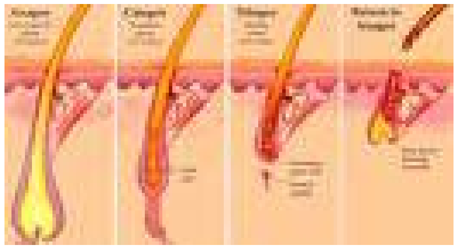
When focused onto a $0.1 mm^2$ area
→ Peak intensity $10^{16} W/cm^2$!!

POWER OFTEN REQUIRED…

Laser cutting and welding

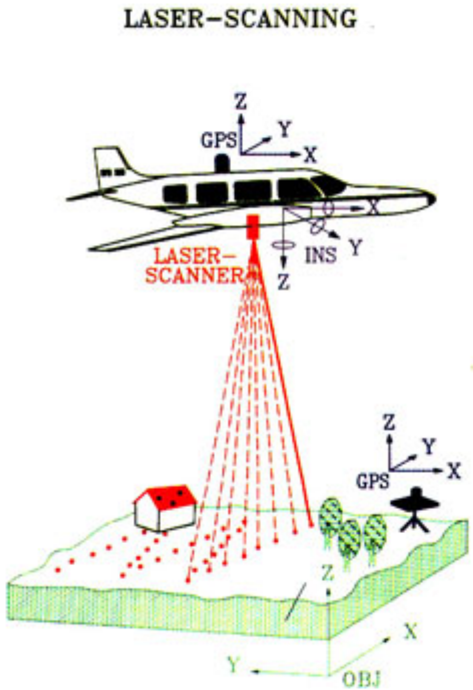
Laser marking and engraving

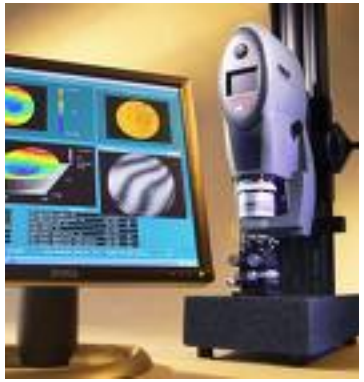
Laser therapy



… BUT NOT ALWAYS NEEDED

Laser scanners





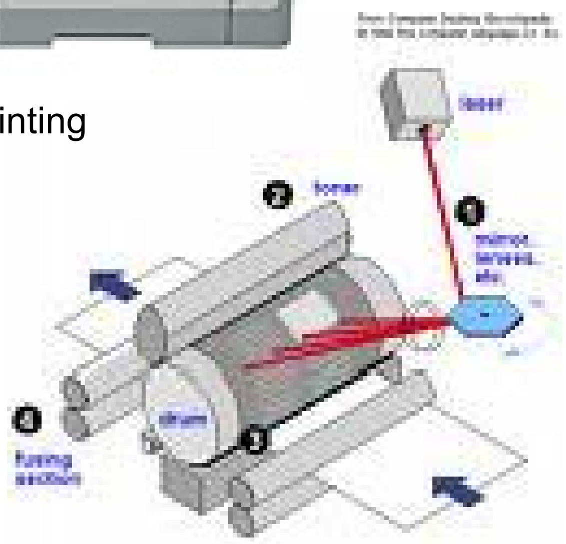
Laser spectrometer

Laser profilometer

LIDAR

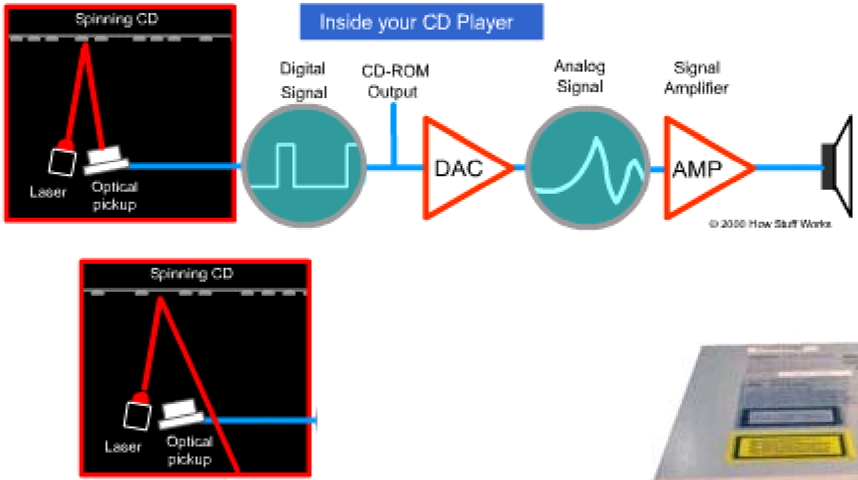
LARGE SCALE APPLICATIONS (LAST TWO DECADES)

Laser printing



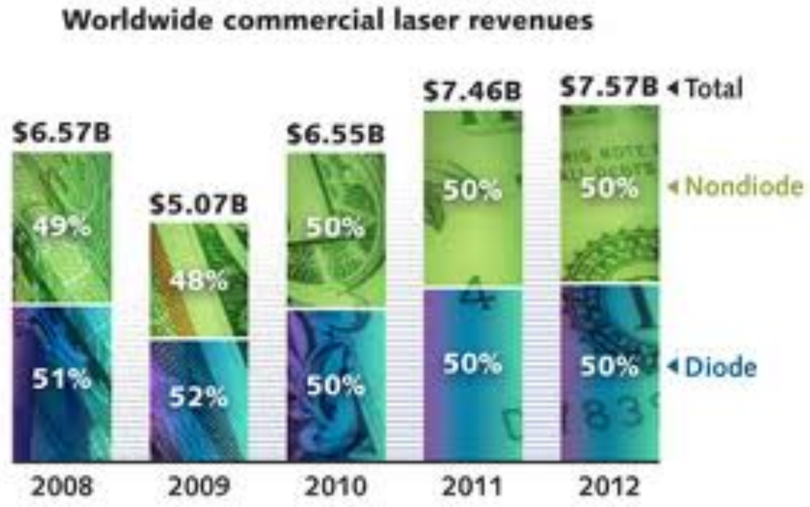
TLC

THE BIG BANG OF LASER DIFFUSION



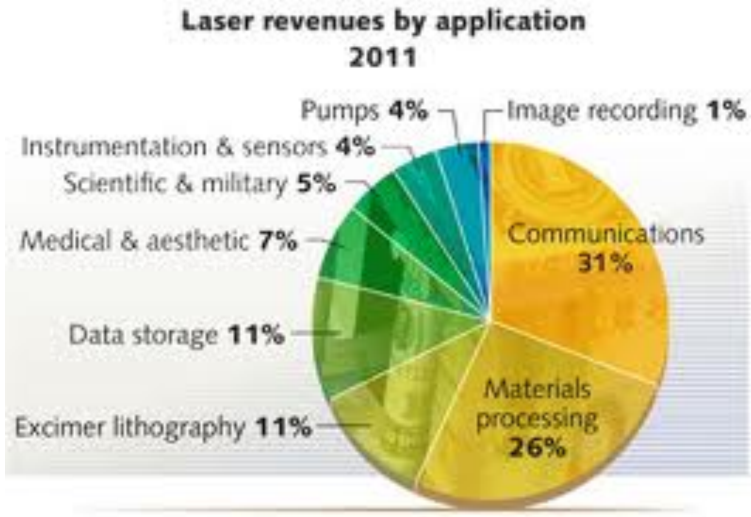
Development of CD readers (later on, CD and DVD readers/writers) pushed the diffusion of lasers into the consumer market

STILL (2012) A GROWING MARKET



While the tremendous diffusion of lasers has experienced a slow-down (weaker data storage market + crisis), forecasts are still optimistic

Specialized laser products (e.g., lasers for lithography and material processing) are high added value items
(relatively few sold, but relatively expensive)



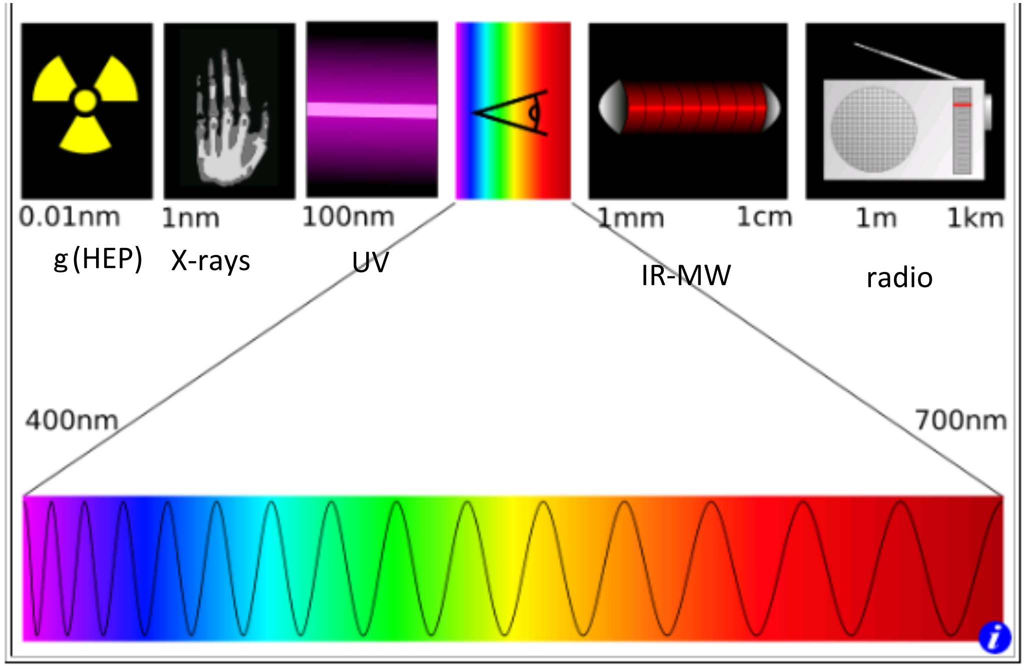
Strong market → strong R&D

WHAT A LASER IS?

(Unconventional) source of e.m. radiation (light):

- ✓ brilliant
- ✓ well colored
- ✓ well collimated

The laser produces **coherent light**

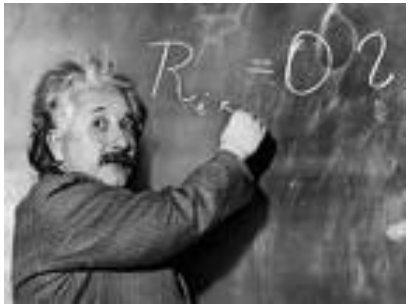


We will restrict to wavelength range:
Minimum l=157 nm (excimer laser for lithography applications)
Maximum l=10.6 mm (CO_2 laser for, e.g., material treatment

Nota: coherent sources do exist, or are strongly searched, able to operate in other regions of the spectrum, e.g., X-ray, e.g., millimiter waves (THz)

LASER AS A SON OF THE XX CENTURY

QUANTUM MECHANICS



RELATIVITY

A STEP BACK: MAXWELL AND WAVES

E.m. wave is a a spatial and temporal varying perturbation of the electric and magnetic fields

Maxwell eqs

$$I)\ \vec{\nabla}\cdot\vec{E}_0=\frac{\rho}{\varepsilon_0}$$
$$II)\ \vec{\nabla}\cdot\vec{B}_0=0$$
$$III)\ \vec{\nabla}\times\vec{E}_0=-\frac{\partial\vec{B}_0}{\partial t}$$
$$IV)\ \vec{\nabla}\times\vec{B}_0=\mu_0\cdot\vec{J}+\varepsilon_0\mu_0\frac{\partial\vec{E}_0}{\partial t}$$

In dielettrico omogeneo e isotropo

$$I)\ \vec{\nabla}\cdot\vec{E}=0$$
$$II)\ \vec{\nabla}\cdot\vec{B}=0$$
$$III)\ \vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$
$$IV)\ \vec{\nabla}\times\vec{B}=\varepsilon\mu\frac{\partial\vec{E}}{\partial t}$$

$$\vec{\nabla}\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$

e applicando il rotore di ambo i membri:

$$\vec{\nabla}\times\vec{\nabla}\times\vec{E}=-\frac{\partial\vec{\nabla}\times\vec{B}}{\partial t}$$

sostituiamo a secondo membro la quarta equazione in luogo di $\vec{\nabla}\times\vec{B}$:

$$\vec{\nabla}\times\vec{B}=\varepsilon\mu\frac{\partial\vec{E}}{\partial t}$$

J = 0 (nel vuoto!)

$$\nabla\times\left(\nabla\times\vec{E}\right)=\nabla\left(\cancel{\nabla\cdot\vec{E}}\right)-\nabla^2\vec{E}$$

ρ = 0 (nel vuoto!)

otteniamo:

$$-\vec{\nabla}^2\cdot\vec{E}=\vec{\nabla}\times\frac{\partial\vec{B}}{\partial t}=-\varepsilon\mu\frac{\partial^2\vec{E}}{\partial t^2}$$

cioè

$$\nabla^2\vec{E}=\varepsilon\mu\frac{\partial^2\vec{E}}{\partial t^2}$$

Analogamente applicando lo stesso procedimento alla quarta equazione otteniamo:

$$\nabla^2\vec{B}=\varepsilon\mu\frac{\partial^2\vec{B}}{\partial t^2}.$$

Wave equations

$$\nabla^2\vec{E}-\varepsilon\mu\frac{\partial^2\vec{E}}{\partial t^2}=0$$
$$\nabla^2\vec{B}-\varepsilon\mu\frac{\partial^2\vec{B}}{\partial t^2}=0.$$

PLANE WAVES

One possible solution of the wave equations is represented by plane waves (harmonic, monochromatic, linearly polarized, in this case):

$$\vec{E}(\vec{r},t) = E_0 e^{i(\vec{k}\bullet\vec{r}-\omega t+\phi)}\hat{e}$$

$$\vec{B}(\vec{r},t) = B_0 e^{i(\vec{k}\bullet\vec{r}-\omega t+\phi)}\hat{b}$$

$$\hat{k} = \hat{e}\times\hat{b}$$

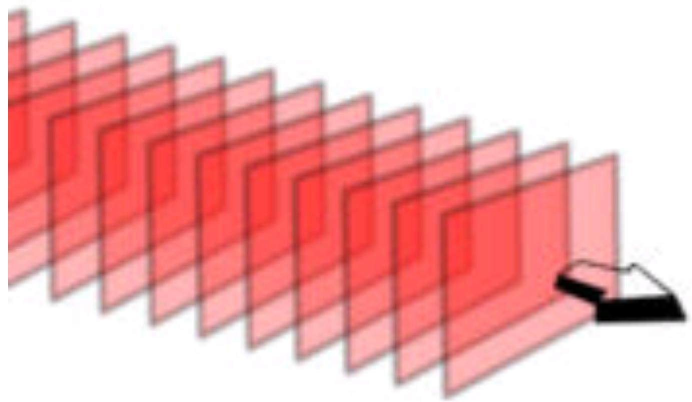
***k** :* wavevector
w : (angular) frequency
E_0, B_0 : field amplitude (with $E_0 = B_0 w/k$)
e, b : field directions (***e***: polarization)

Note: the representation is in the complex plane, but effects are linked to the real-part!!

Plane wave propagating along the positive *Y* direction:

$$\vec{E}(x,t) = E_0 e^{i(kx-\omega t+\phi)}\hat{y}$$

$$\vec{B}(x,t) = B_0 e^{i(kx-\omega t+\phi)}\hat{z}$$



Wave fronts (surfaces where *E(t)* is uniform) are planes orthogonal to ***k***
Propagation: in practice, the wave front move with $v_{fase}=w/k$

POYNTING VECTOR AND INTENSITY

Poynting vector (in a vacuum):

$\mathbf{S} = \mathbf{E} \times \mathbf{B}/\mu_0$

But, for a plane wave (due to Maxwell):

$\mathbf{B} = \mathbf{k} \times \mathbf{E} \rightarrow B = E/c$ (in a vacuum)

Hence:

$S = E^2/(c\mu_0) = c\varepsilon_0 E^2$

According to the Poynting's theorem, the flux of ***S*** across a surface represents the energy per unit time crossing that surface

The Poynting vector is parallel to ***k***

The time-averaged (over a period) module of *S* indicates the flow of energy per unit time transported by the wave along the propagation direction
One gets:

$<|S|> = c\, \varepsilon_0 E_0^2/2$

That corresponds to the so-called **intensity** of the e.m. wave *(units are W/m^2)*

DEFINITIONS AND RELATIONSHIPS

La soluzione di queste equazioni è un'onda che si propaga con velocità costante:

$$v = \frac{1}{\sqrt{\varepsilon\mu}}$$

Per Maxwell!!

Nel vuoto questa velocità diventa la velocità della luce:

$$c = \frac{1}{\sqrt{\varepsilon_0\mu_0}}.$$

Si chiama **fronte d'onda** il luogo dei punti tali che, ad un certo istante, la soluzione delle equazioni delle onde assume valore costante. A seconda della possibilità di modellizzare l'onda a seconda della forma del suo fronte d'onda possiamo chiamare onda rettilinea se i suoi fronti d'onda sono rettilinei, circolare se i suoi fronti d'onda sono circolari e onda piana se i suoi fronti d'onda sono piani, infine, onda sferica se i suoi fronti d'onda sono superfici sferiche.

$v_{fase} = c/n$

n : index of refraction (real part – we'll see more on that!)

$n = \sqrt{\varepsilon_R}$ (with ε_R real)

(for the typical situations in optics, one has $\mu_R=1$)

λ : wavelength (distance between two adjacent wavefronts)
T : period of time needed to a wavefront in order to displace by l

$$v = \frac{\lambda}{T}$$ dove si ritrova la velocità di fase cioè la nostra velocità di propagazione dell'onda.

Altre proprietà dell'onda sinusoidale sono:

$$\nu = \frac{1}{T}$$ la frequenza;

$$\omega = 2\pi\nu = \frac{2\pi}{T}$$ la **pulsazione**;

$$\vec{k} = \frac{2\pi}{\lambda}$$ il **numero d'onda** o **vettore d'onda** che rappresenta la direzione di propagazione dell'onda.

In the visible (and vacuum):
$\lambda \sim 350\text{-}750$ nm
⇩
$\nu \sim 10^{14}\text{-}10^{15}$ Hz

A FEW UNIQUE FEATURES OF LASER LIGHT

CONVENTIONAL LIGHT
(e.g., bulb lamp)

Weakly directional
Non monochromatic
Non coherent
Low power

LASER LIGHT

Highly directional
Ideally monochromatic
Coherent
High power possible

What coherence is??
(first glance, we'll come back on that)

PLANE WAVES AND LASERS

$$\vec{E}(x,t) = E_0 e^{i(kx-\omega t+\phi)}\hat{y}$$

Wavefunction:
plane: wavefront (well fit with good lasers)
harmonic: periodical oscillations (ok for any source)
progressive: propagates energy (ok for any source)
monochromatic: single color (as in ideal lasers)

The description of laser light through plane waves is rather accurate:

- ✓ Monochromaticity (it cannot be fully monochromatic, but in case Fourier analysis can be used)
- ✓ Perfect collimation (it cannot be fully collimated, that is the wavevector cannot be aligned along one axis, but lasers can approximate well such a situation)

But indefinite wavefronts (i.e., infinite waveplanes) are for sure not realistic!

WAVEPACKETS

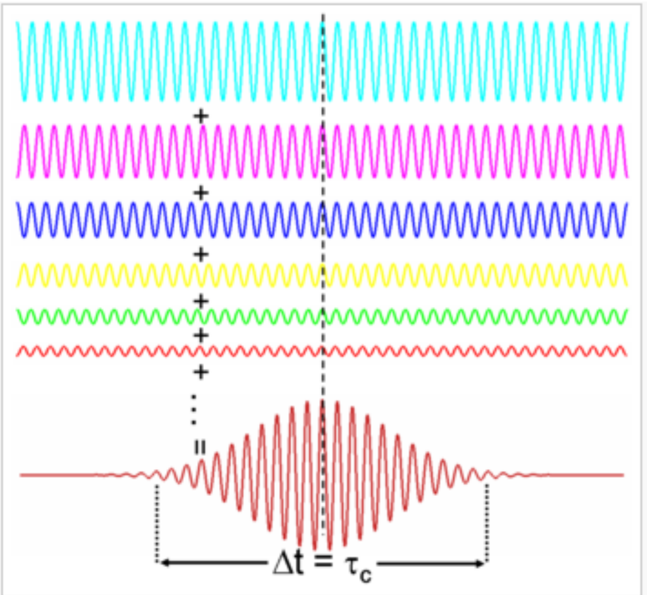
Uncertainty principle (Heisenberg, or mathematics of Fourier trasnform) says:

$$\Delta X \Delta P \geq \frac{\hbar}{2}. \qquad \Delta x \Delta k \geq \frac{1}{2} \qquad \Delta E \Delta t \gtrsim \frac{\hbar}{2}, \qquad \Delta \omega \Delta t \geq \frac{1}{2}$$

A wave packet is a localized disturbance that results from the sum of many different wave forms. If the packet is strongly localized, more frequencies are needed to allow the constructive superposition in the region of localization and destructive superposition outside the region. From the basic solutions in one dimension, a general form of a wave packet can be expressed as

$$u(x,t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} A(k)\ e^{i(kx-\omega(k)t)}\ dk.$$

with $A(k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} u(x,0)\ e^{-ikx}\ dx.$

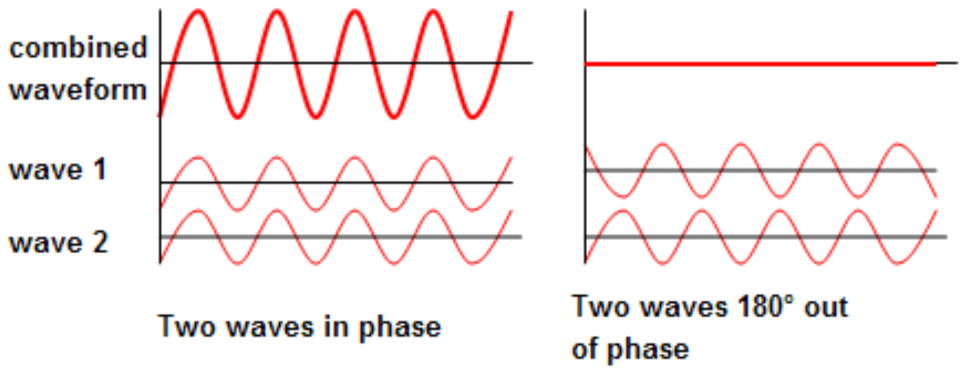


A wavepacket is obtained by superposing (many) waves with different frequencies (coherent each other, we'll see the meaning)

A wavepacket is localized in time and space (as it should be because of Heisenberg)

INTERFERENCE I

In physics, **interference** is the addition (superposition) of two or more waves that result in a new wave pattern. **Interference** usually refers to the interaction of waves which are correlated or coherent with each other, either because they come from the same source or because they have the same or nearly the same frequency.



Quanto detto risulta evidente nella trattazione analitica del problema, nel caso particolare di due onde armoniche A_1 e A_2, entrambe di ampiezza a, che vibrano con la stessa frequenza w e risultano sfasate di un angolo pari a g:

A_1 = a cos(wt); A_2 = a cos(wt + g)

Per il principio di sovrapposizione, l'onda risultante è data dalla somma delle due:

$A_{tot} = A_1 + A_2 =$ (2a cosg/2) cos(wt + g/2)

Nell'espressione analitica dell'onda risultante A_{tot} (che si ottiene applicando le formule di prostaferesi per la somma di coseni), si possono individuare due fattori significativi: (2a cos g/2), che rappresenta l'ampiezza, e cos (wt + g/2), che esprime la dipendenza dal tempo. Da questo secondo fattore si evince che l'onda risultante vibra con la stessa frequenza delle due onde sovrapposte; dal primo, invece, si deduce che l'ampiezza risultante può variare tra 0 e 2a (il coseno è una funzione trigonometrica che varia tra 0 e 1), a seconda dello sfasamento g: è 0 quando g/2 vale 90°, cioè quando g è 180°, il che corrisponde al caso dell'interferenza distruttiva; è massimo quando g = 0, vale a dire quando le onde vibrano in fase, e si ha interferenza costruttiva.

INTERFERENCE II

Usually we are only interested in $E_0^{\ 2}$ (to get the intensity), so we can simply multiply each side of the above equation by its corresponding complex conjugate, using the fact that $e^{i\phi} \cdot e^{-i\phi} = 1$:

$$E_0^{\ 2} = (E_{0_1} + E_{0_2} e^{i\delta})(E_{0_1} + E_{0_2} e^{-i\delta})$$
$$= E_{0_1}^{\ \ 2} + E_{0_2}^{\ \ 2} + E_{0_1} E_{0_2} (e^{i\delta} + e^{-i\delta})$$

Using Euler's theorem we see that the ( ) in the last term is $2\cos\delta$, so we have

$$E_0^{\ 2} = E_{0_1}^{\ \ 2} + E_{0_2}^{\ \ 2} + 2E_{0_1} E_{0_2} \cos\delta \,.$$

This equation allows us to relate the intensity of the combined wave to the intensities of the original waves alone and the phase difference δ. We use the fact that for any e-m wave $I = KE_0^{\ 2}$, where (if we are talking about average intensity over a cycle) $K = \frac{1}{2} c\varepsilon_0$.

We multiply every term of the above equation by K. Denoting the intensities of the original waves by I_1 and I_2, and calling the intensity of the combined wave I, we find:

Interference of two waves	$I = I_1 + I_2 + 2\sqrt{I_2 I_2} \cos\delta$

Remember:

Euler's theorem	$e^{i\theta} = \cos\theta + i\sin\theta$

COHERENCE I

In physics, **coherence** is a property of waves, that enables stationary (i.e. temporally and spatially constant) interference. More generally, coherence describes all correlation properties between physical quantities of a wave.

$$\Delta\omega\Delta t \geq \frac{1}{2}$$

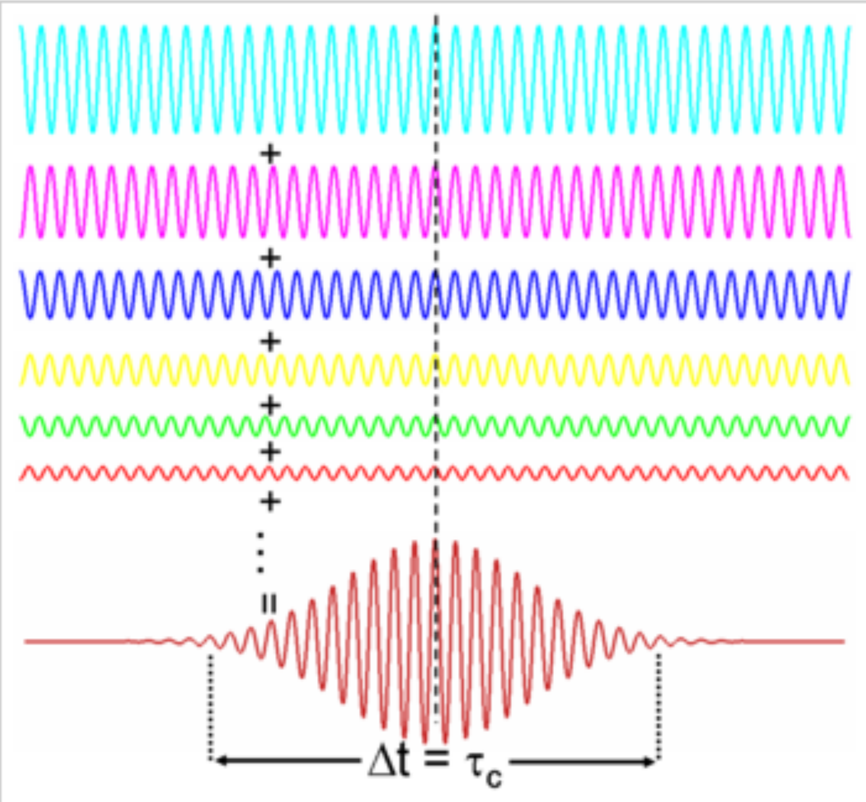


Figure 10: Waves of different frequencies (i.e. colors) interfere to form a pulse if they are coherent.

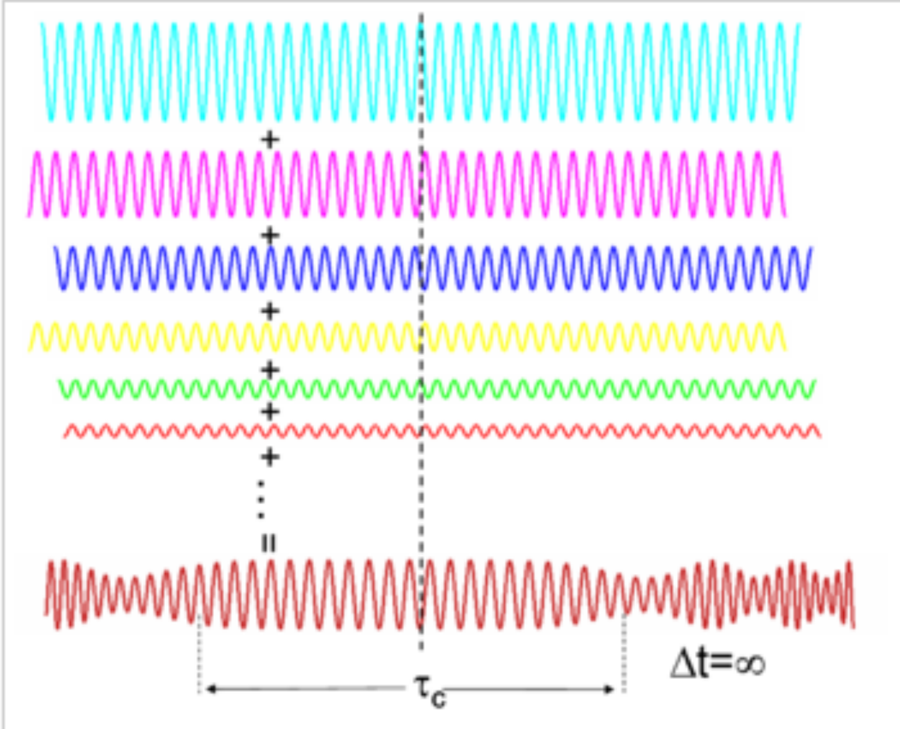


Figure 11: Spectrally incoherent light interferes to form continuous light with a randomly varying phase and amplitude

Coherence makes possible to obtain a wavepacket, by ensuring a constant relationship between the phase of the added waves

Spectral coherence

COHERENCE II

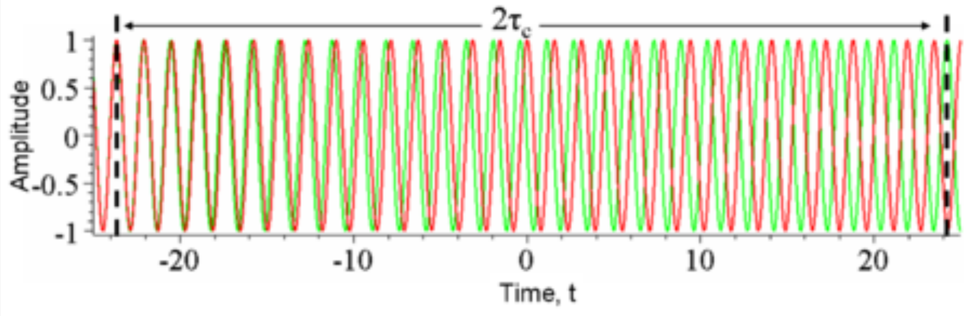


Figure 2: The amplitude of a wave whose phase drifts significantly in time τ_c as a function of time *t* (red) and a copy of the same wave delayed by $2\tau_c$ (green). At any particular time t the wave can interfere perfectly with its delayed copy. But, since half the time the red and green waves are in phase and half the time out of phase, when averaged over t any interference disappears at this delay.

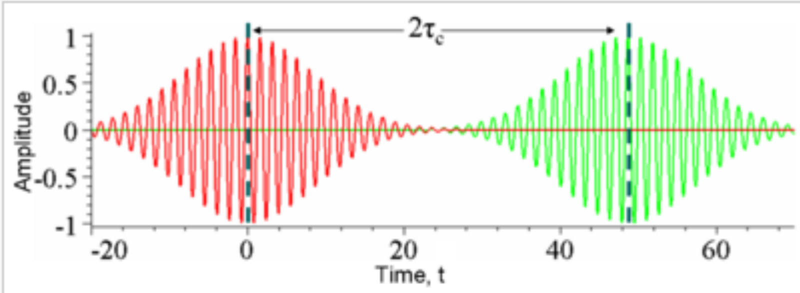


Figure 3: The amplitude of a wavepacket whose amplitude changes significantly in time τ_c (red) and a copy of the same wave delayed by $2\tau_c$ (green) plotted as a function of time *t*. At any particular time the red and green waves are uncorrelated; one oscillates while the other is constant and so there will be no interference at this delay. Another way of looking at this is the wavepackets are not overlapped in time and so at any particular time there is only one nonzero field so no interference can occur.

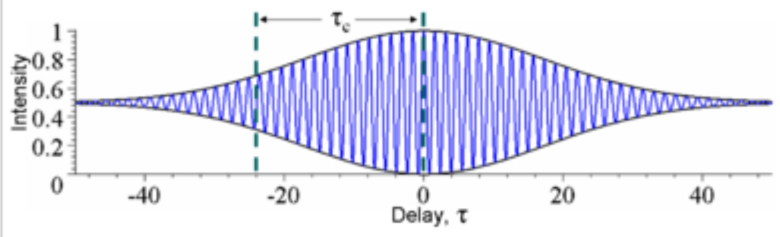


Figure 4: The time-averaged intensity (blue) detected at the output of an interferometer plotted as a function of delay τ for the example waves in Figures 2 and 3. As the delay is changed by half a period, the interference switches between constructive and destructive. The black lines indicate the interference envelope, which gives the degree of coherence. Although the waves in Figures 2 and 3 have different time durations, they have the same coherence time.

Somewhere (at a fixed position) a constant relationship between the phase of different waves is found

Temporal coherence

COERENZA III

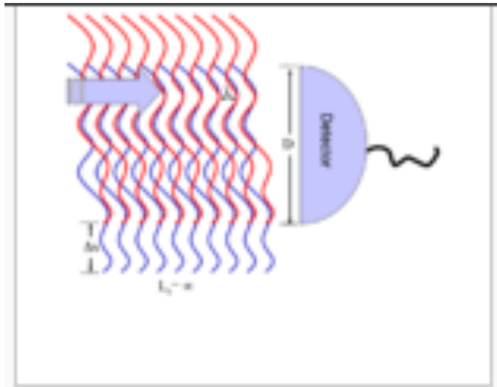


Figure 9: A wave with infinite coherence area is combined with a spatially-shifted copy of itself. Some sections in the wave interfere constructively and some will interfere destructively. Averaging over these sections, a detector with length D will measure reduced interference visibility. For

Spatial coherence
(examples)

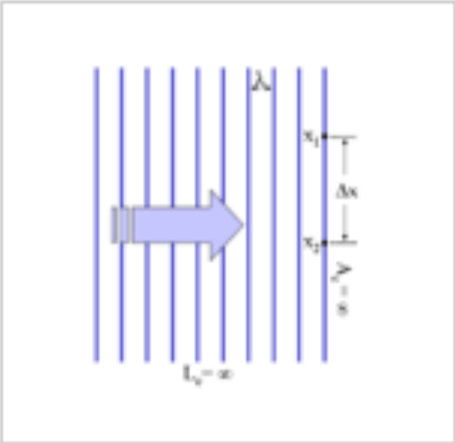


Figure 5: A plane wave with an infinite coherence length.

In two different places at any time a relationship between the phase is found

Coherence will be better understood when looking more closely to interference and related phenomena

CONCLUSIONS

Laser is a source of radiation with unconventional (unique) features

A huge amount of applications has been found and a huge amount of research has been carried out with/on lasers (still growing up)

Electromagnetic waves of the simplest form, i.e., plane waves, are adequate for a classical description of laser light (with some restriction)

By itself, the classical description is not enough to understand either the laser operation or its unique properties

Being a son of the XX century, the laser requires for its interpretation some quantum mechanics (very basic)

CREDITS

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