Lasers

2017/2018, lecture 1

Czesław Radzewicz

Lasers 2017/2018

General Information:

1. size: 2h/week
2. exercises: NO
3. homework: not obligatory, counts for the final mark

Grading:

1. Written examination: YES, test + problems
2. Oral examination: NO
3. Final grade: homework-0.25, examination test – 0.25, egzamination problems – 0.5
4. Satisfactory > 50%

content:

1. Non-resonant and resonant light-matter interaction, classical and semiclassical approach
2. Spectral line broadening,
3. Light amplification: unsaturated, saturated, basic laser media schemes, pumping
4. Gaussian beams, optical cavities,
5. Laser oscillator: threshold condition, output power
6. Laser dynamics: relaxation oscillations, Q-switching, mode-lockinkg,
7. Selected laser types,
8. Nonlinear optics; harmonics generation, optical parametric amplifiers and oscillators
9. Examples of laser applications.

what do I hope for:

To provide physical foundations for the operation of laser amplifiers and oscillators. It IS NOT a theoretical lecture – we will pay attention mostly to practical aspects of lasers. Thus the mathematics will be kept as simple as possible just sufficient to provide insight into key aspects of lasers. Classical approach will dominate; we will use semiclassical approach only to describe light-matter interaction. I will cover some experimental techniques (methods and instruments).

fundamentals:

A. Siegman, Lasers
B. Eberly & Miloni, Laser Physics

some history:

1. **MASER** (**M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation),

- 1952, Nikolay Basov i Aleksandr Prokhorov, Lebiediev Institute of Physics – theory
- 1953 Charles H. Townes, J. P. Gordon, and H. J. Zeiger, Columbia University – practical realization

from the left:
J.P. Gordon,
N. G. Basov,
H. J. Zeiger,
M. Prokhorov
C. H. Townes

some history, cont.

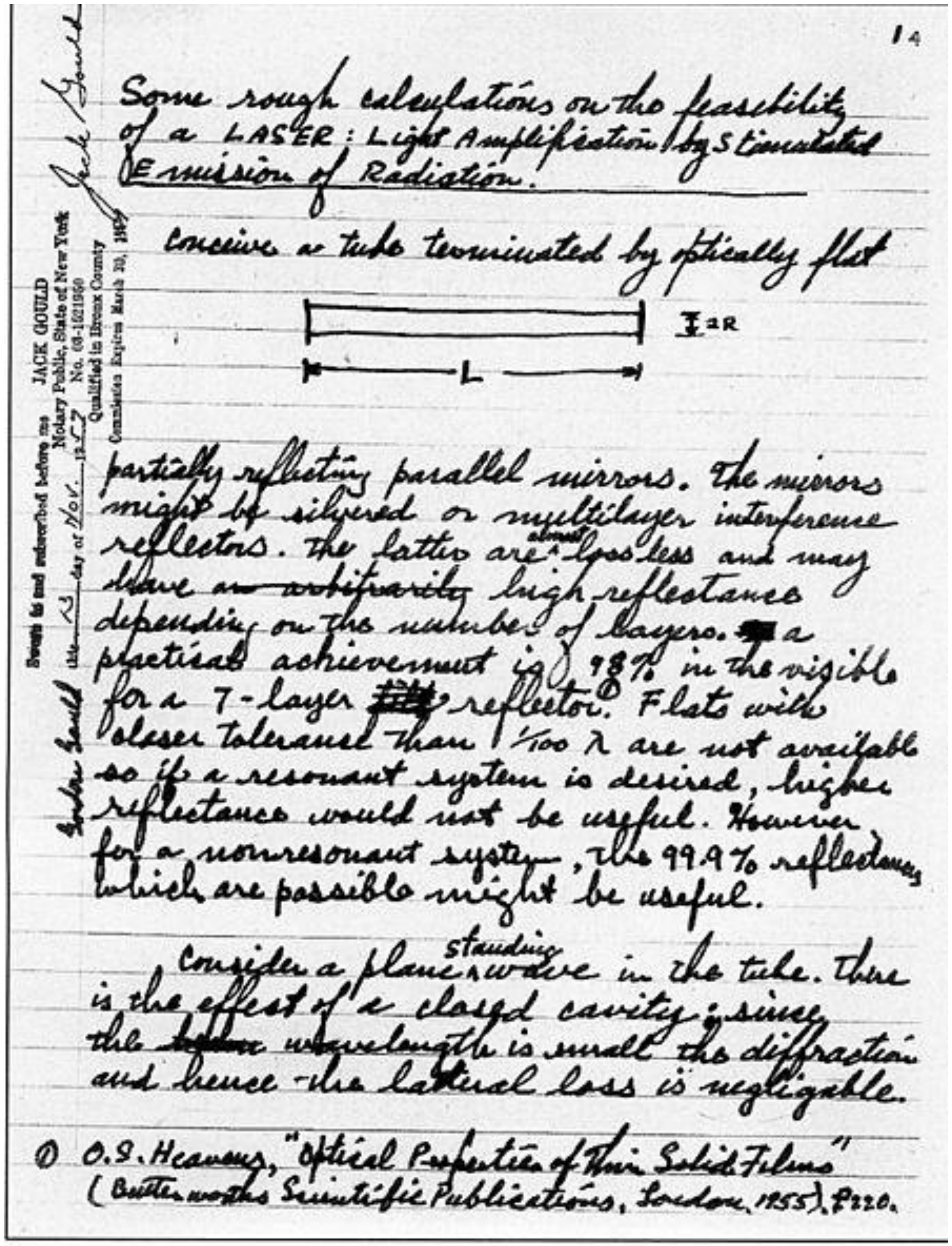
1. **LASER** (ang. **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation),

- 1958, Charles Hard Townes i Arthur Leonard Schawlow, Bell Labs – patent and Phys. Rev. **112**, …
- Charles H. Townes i G. Gould start to collaborate at the Columbia University

Charles H. Townes
1915-

Gordon Gould, 1920-2005

Arthur Leonard Schawlow
(1921-1999)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Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation.

Conceive a tube terminated by optically flat

partially reflecting parallel mirrors. The mirrors might be silvered or multilayer interference reflectors. The latter are almost loss-less and may have an arbitrarily high reflectance depending on the number of layers. a practical achievement is 98% in the visible for a 7-layer reflector.① Flats with closer tolerance than 1/100 λ are not available so if a resonant system is desired, higher reflectance would not be useful. However for a nonresonant system, the 99.9% reflectances which are possible might be useful.

Consider a plane standing wave in the tube. There is the effect of a closed cavity; since the wavelength is small the diffraction and hence the lateral loss is negligible.

① O.S. Heavens, "Optical Properties of Thin Solid Films" (Butterworths Scientific Publications, London, 1955), p.220.

Sworn to and subscribed before me this 13 day of Nov. 1957

JACK GOULD
Notary Public, State of New York
No. 03-1621950
Qualified in Bronx County
Commission Expires March 30, 1959

Jack Gould

Gordon Gould

Patent debate

Gould vs Townes & Schawlow

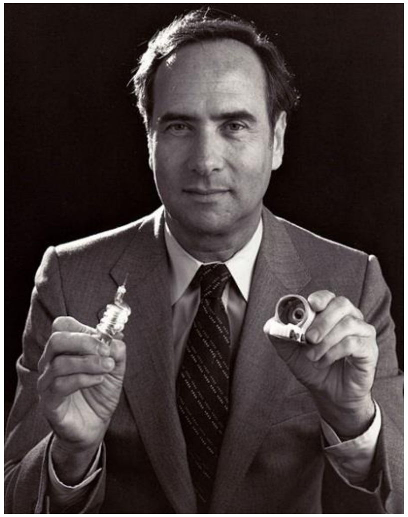
1987: Federal Court rules:

Gould has the patent for gas lasers and optical pumping

some history, cont.

1. 1960, T. H. Maiman, Hughes Research Laboratories, the first laser (ruby)

- 1960, Ali Javan i W. R. Bennett, Massachusetts Institute of Technology – the first He-Ne laser (3,39μm)



Theodore Harold Maiman
1927-2007

Ali Javan
1926 -

Wiliam R. Bennett
1930-2008

some history, cont.

1964

Charles H. Townes
1915-

Nicolay Gennadiyevich Basov
1922-2001

Alexander Prokhorov
1916-2002

The Nobel Prize in Physics 1964 was divided, one half awarded to Charles Hard Townes, the other half jointly to Nicolay Gennadiyevich Basov and Aleksandr Mikhailovich Prokhorov *"for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle*

This is not the end of the story!

Alfred Kastler
The Nobel Prize in Physics **1966** was awarded to Alfred Kastler *"for the discovery and development of optical methods for studying Hertzian resonances in atoms"*.

Dennis Gabor
The Nobel Prize in Physics **1971** was awarded to Dennis Gabor *"for his invention and development of the holographic method"*.

Nicolaas Bloembergen
Arthur Leonard Schawlow
Kai M. Siegbahn
The Nobel Prize in Physics 1981 was divided, one half jointly to Nicolaas Bloembergen and Arthur Leonard Schawlow *"for their contribution to the development of laser spectroscopy"* and the other half to Kai M. Siegbahn *"for his contribution to the development of high-resolution electron spectroscopy"*.

Norman F. Ramsey
Hans G. Dehmelt
Wolfgang Paul

The Nobel Prize in Physics 1989 was divided, one half awarded to Norman F. Ramsey *"for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks"*, the other half jointly to Hans G. Dehmelt and Wolfgang Paul *"for the development of the ion trap technique"*.

Steven Chu
Claude Cohen-Tannoudji
William D. Phillips

The Nobel Prize in Physics 1997 was awarded jointly to Steven Chu, Claude Cohen-Tannoudji and William D. Phillips *"for development of methods to cool and trap atoms with laser light"*.

Eric A. Cornell
Wolfgang Ketterle
Carl E. Wieman

The Nobel Prize in Physics 2001 was awarded jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman *"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"*.

Roy J. Glauber
John L. Hall
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"*.

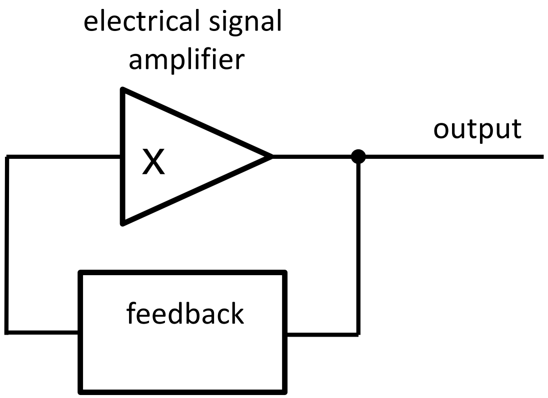
Charles Kuen Kao
Willard S. Boyle
George E. Smith
The Nobel Prize in Physics 2009 was divided, one half awarded to Charles Kuen Kao *"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"*, the other half jointly to Willard S. Boyle and George E. Smith *"for the invention of an imaging semiconductor circuit – the CCD sensor"*.

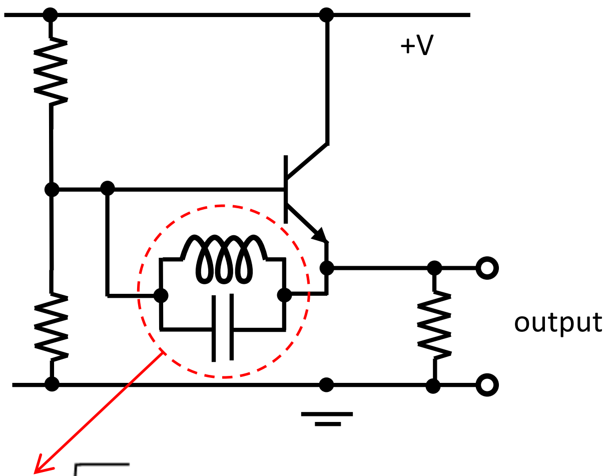
Serge Haroche
David J. Wineland
The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland *„for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"*

Eric Betzig
Stefan W. Hell and
William E. Moerner
The Nobel Prize in Chemistry 2014 was awarded jointly to "for the development of super-resolved fluorescence microscopy".

……. ?

electronics oscillator



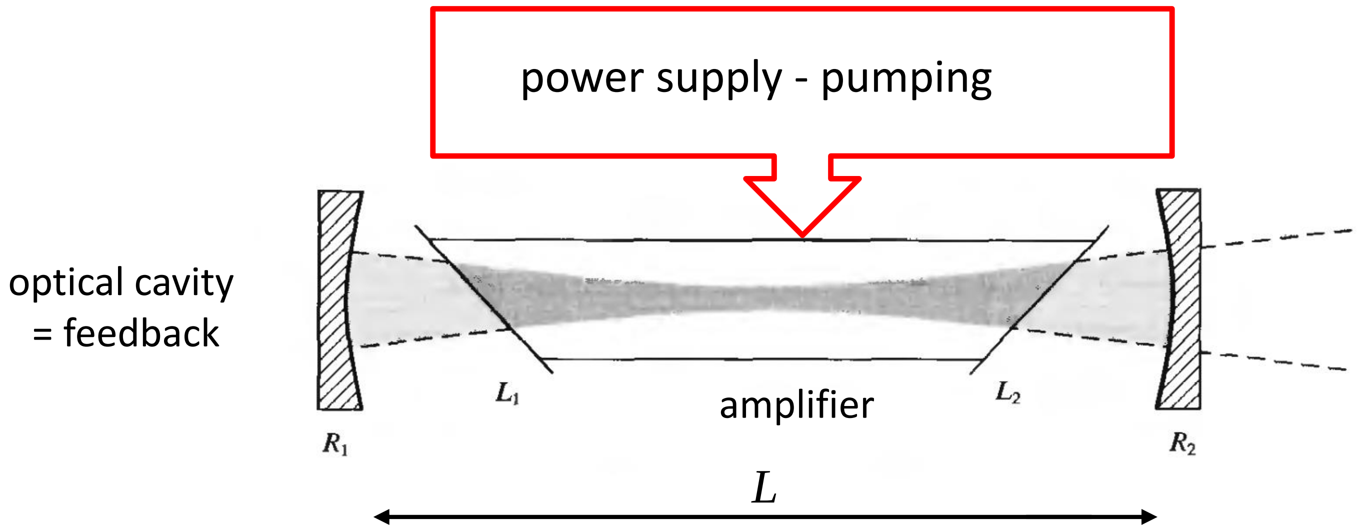


$$\omega = \sqrt{\frac{1}{LC}}$$

1. amplifier
2. feedback
3. power supply

typically: amplifier size << λ

optical oscillator – a laser



- typically: $L >> \lambda$
- cavity – open resonator

unique properties of the laser light

light bulb, Thomas Edison, 1879

?

⇔

laser, Gordon Gould, 1960

coherence of light:

first-order correlation function

$$G(\boldsymbol{r}_1, \boldsymbol{r}_2, t_1, t_2) = \langle E(r_1, t_1) E^*(r_2, t_2) \rangle$$

normalized space correlation function

$$g(\boldsymbol{r}_1, \boldsymbol{r}_2) = \frac{\langle E(r_1, t) E^*(r_2, t) \rangle_t}{\sqrt{I(\boldsymbol{r}_1) I(\boldsymbol{r}_2)}}$$

normalized time correlation function

$$g(t_1, t_2) = \frac{\langle E(t_1) E^*(t_2) \rangle}{\langle E(t) E^*(t) \rangle_t}$$

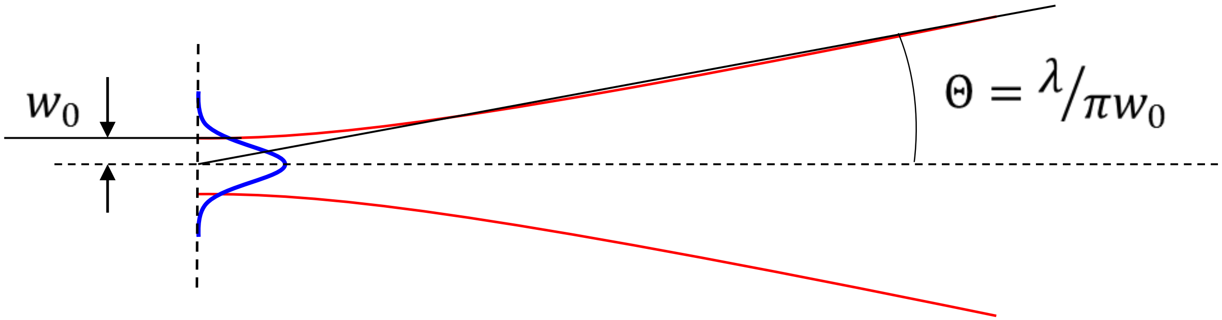
for ergodic processes:

$$g(\tau) = \frac{\langle E(t) E^*(t + \tau) \rangle_t}{\langle E(t) E^*(t) \rangle_t}$$

laser light properties:

1. very good spatial coherence ➔ small beam divergence

complete spatial coherence – phases are perfectly correlated across the entire cross-section of the beam, for example, in the Gaussian beam



numbers:

- He-Ne laser, λ=0.63μm, w_0 = 1mm, $\Theta \cong 0.2\ mrad$
- He-Ne laser, λ=0.63μm, w_0 = 100mm, $\Theta \cong 2\ \mu rad$

M^2 parameter

M^2:

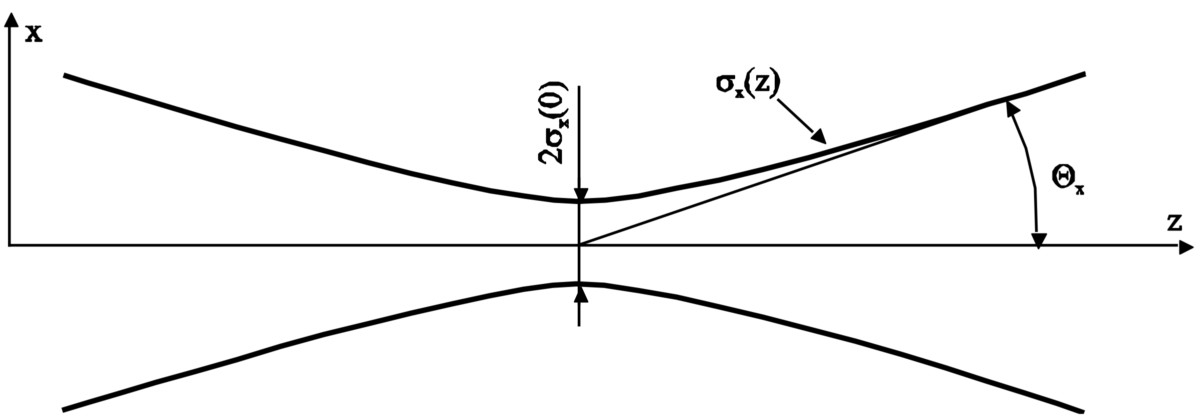
1. define the dispersion of the position in the beam waist

$$\sigma_x = \sqrt{\frac{\int x^2 I(x,y,0)dxdy}{\int I(x,y,0)dxdy}}, \sigma_y = \sqrt{\frac{\int y^2 I(x,y,0)dxdy}{\int I(x,y,0)dxdy}}$$

From **Fraunhoffer diffraction** we know that**:** in the far field the shape of intensity distribution is preserved – the size of the beam grow linearly with the distance from waist $I(x,y,Mz) = \frac{1}{M^2} I(x,y,z)$.

2. define beam's divergence angle and determine the variance of this angle:

$$\Theta_x = \lim_{z\to\infty} \sqrt{\frac{\int {\Theta_x}^2 I(\Theta_x,\Theta_y,z)d\Theta_x d\Theta_y}{\int I(\Theta_x,\Theta_y,z)d\Theta_x d\Theta_y}}, \Theta_y = \lim_{z\to\infty} \sqrt{\frac{\int {\Theta_y}^2 I(\Theta_x,\Theta_y,z)d\Theta_x d\Theta_y}{\int I(\Theta_x,\Theta_y,z)d\Theta_x d\Theta_y}}$$



The product of beam parameters is called M^2

Gaussian beam minimizes M^2

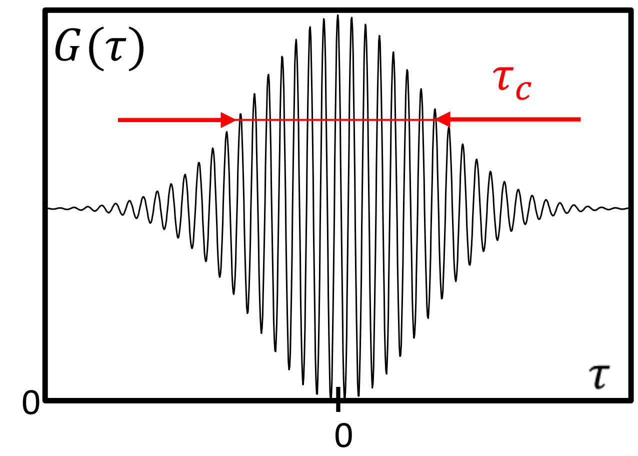
$$\sigma_G \Theta_G = \lambda/\pi$$

For any other beam with given σ and Θ the M2 parameter defined as the ratio

$$M^2 = \frac{\sigma\Theta}{\sigma_G\Theta_G} > 1$$

laser light properties, cont.:

2. Spectrum and temporal coherence mHz-PHz, s-fs



temporal coherence function

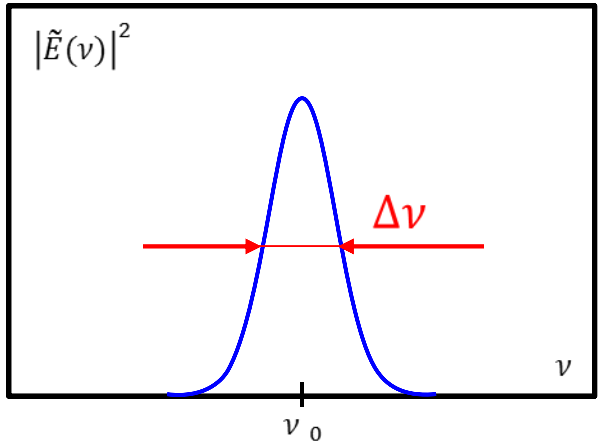
$$G(\tau) = \langle E(t)E^*(t+\tau)\rangle_t$$

Wiener-Kchinchin theorem:

defining:

$G(\tau) = \int_{-\infty}^{\infty} E(t)E^*(t+\tau)dt$ and $\tilde{E}(\nu) = \int_{-\infty}^{\infty} E(t)e^{-i2\pi\nu t}dt$

the following is true: $\left|\tilde{E}(\nu)\right|^2 = \int_{-\infty}^{\infty} G(\tau)e^{-i2\pi\nu t}d\tau$



Fourier limit: the rule of thumb relation:

$$\Delta\nu \cong {}^1/_{\tau_c}$$

Numbers:

$\Delta\nu = 1\text{ mHz} \Leftrightarrow \tau_c \cong 10^3\text{ s}, l_c \cong 3\cdot 10^{11}\text{m}$

$\Delta\nu = 100\text{ THz} \Leftrightarrow \tau_c \cong 10\cdot 10^{-15}\text{ s}, l_c \cong 3\cdot 10^{-6}\text{ m}$

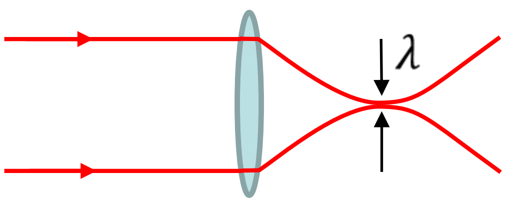
laser light properties, cont.:

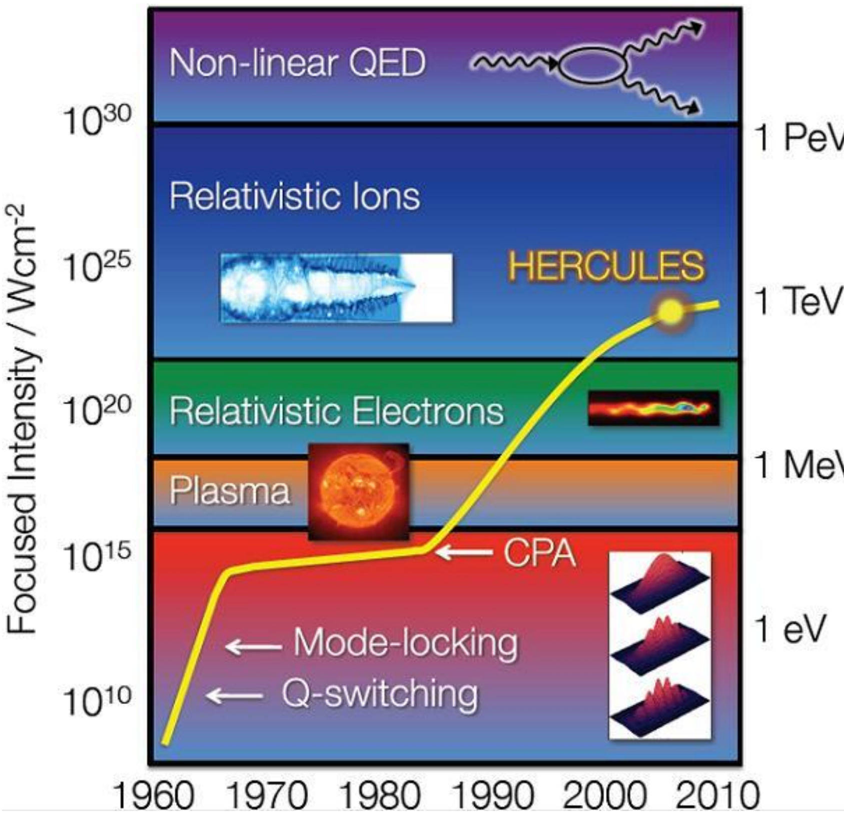
3. pulses; we can get femtosecond (10^{-15} s) pulses directly from lasers. High harmonics generation of laser light gives attosecond (10^{-18} s) pulses.

4. average power; up to 100 kW in continuous operation (cw) regime. MW power levels feasible in the future

5. Peak power; multi-PW (1PW=10^{15}W) facilities are available. Exawatt (1EW=1018W) systems are planned, i.e. Extreme Light Infrastructure (ELI)

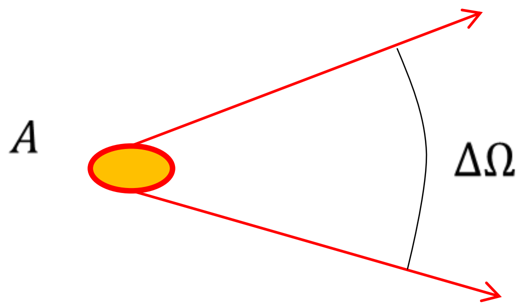
5. Peak intensity involves peak power and focusibilty.





laser light properties, cont.:

7. Spectral intensity



power

$$\beta_\nu = \frac{P}{A\,\Delta\Omega\,\Delta\nu}$$

source area

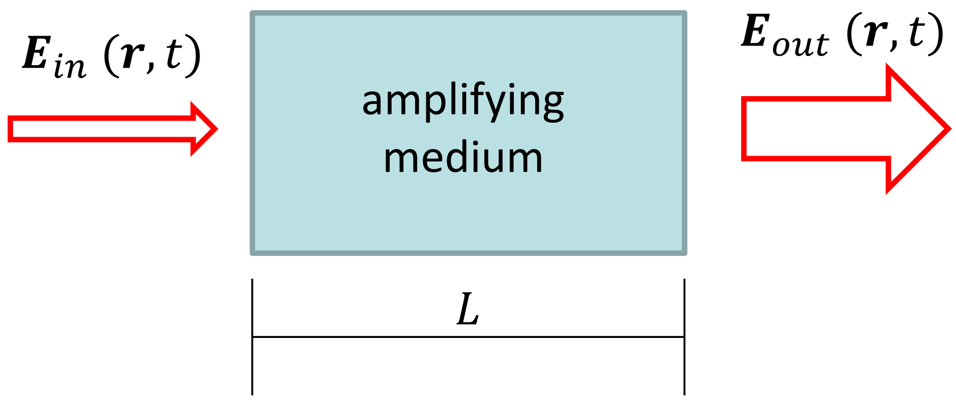
solid angle

spectral bandwidth

numbers:

- super single-mode laser: 1W, 1mHz, $A\Delta\Omega = \lambda^2 \Longrightarrow \beta_\nu \cong 10^{11}[\mathrm{cm}^2 \cdot \mathrm{Hz} \cdot \mathrm{strad}]^{-1}$
- Typical CPA system: 100fs, 1PW, $A\Delta\Omega = \lambda^2 \Longrightarrow \beta_\nu \cong 10^{10}[\mathrm{cm}^2 \cdot \mathrm{Hz} \cdot \mathrm{strad}]^{-1}$

light amplification



$$\boldsymbol{E}_{in}(r,t) = \boldsymbol{A}e^{i(\omega t - kz)}$$

ideal amplifier:

$$\boldsymbol{E}_{out}(r,t) = G'\boldsymbol{A}e^{i[\omega t - k(z+L)]}$$

(amplitude) amplification

real amplifier:

$$\boldsymbol{E}_{out}(r,t) = G\boldsymbol{A}e^{-i[\omega t - k(z+L)]} + \underbrace{\int \boldsymbol{E}(\xi)e^{i\left[(\omega+\xi)t - \left(\boldsymbol{k}+\boldsymbol{\Delta k}(\xi)\right)\cdot \boldsymbol{r} - \varphi(\xi)\right]}\,d\xi}_{\text{noise}}$$

no-cloning theorem
Wooters, Żurek, and Dieks

no-cloning

We have a system A is in a given state ψ $|\psi\rangle_A$. We want to transform another system B in the state φ $|\varphi\rangle_B$ into $|\psi\rangle_B$

Assumptions:

- $|\varphi\rangle_B$ is not correlated to $|\psi\rangle_A$
- we know nothing about $|\psi\rangle_A$
- the method must be universal – it should work for any state of A: $|\xi\rangle_A$

the state of the total system is: $|\psi\rangle_A |\varphi\rangle_B$
we can aplly any unitary operator: $U(t) = e^{iHt/\hbar}, \quad U^\dagger U = 1$

we want: $U|\psi\rangle_A |\varphi\rangle_B = |\psi\rangle_A |\psi\rangle_B$
and $U|\xi\rangle_A |\varphi\rangle_B = |\xi\rangle_A |\xi\rangle_B$
for any ψ i ξ.

$$\langle\varphi|_B \langle\xi|_A \quad |\psi\rangle_A |\varphi\rangle_B = \langle\varphi|_B \langle\xi|_A U^\dagger U |\psi\rangle_A |\varphi\rangle_B = \langle\xi|_B \langle\xi|_A |\psi\rangle_A |\psi\rangle_B$$

$$\langle\xi|\psi\rangle = \langle\xi|\psi\rangle^2$$

Since $|\psi\rangle$ and $|\xi\rangle$ are arbitrary this is not always true

Quantum cloning is never perfect:
it comes with errors - noise

W. K. Wootters and W. H. Zurek, A single quantum cannot be cloned, *Nature* **299,** 802-803 (1982)