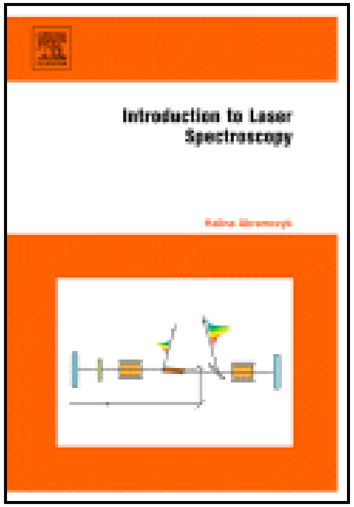


Introduction to Laser Spectroscopy

SPH 618
Optical and Laser Physics
University of Nairobi, Kenya
Lecture 3
MODE LOCKING AND Q-SWITCHING

Prof. Dr Halina Abramczyk

Max Born Institute for Nonlinear Optics and Ultrashort Laser Pulses, Berlin, Germany,

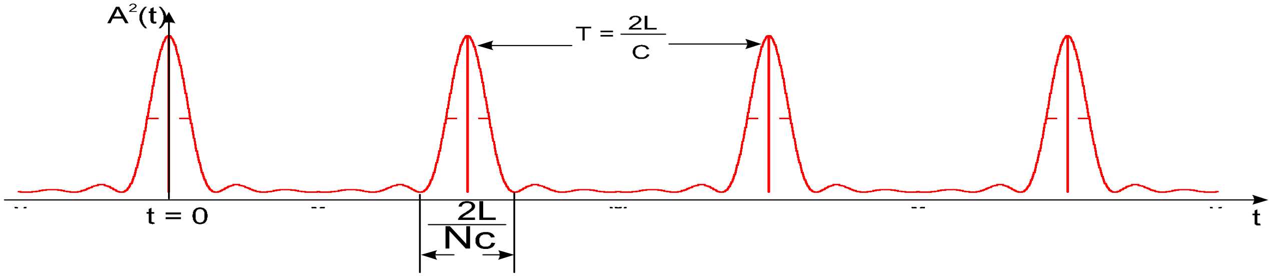
Technical University of Lodz, Lodz, Poland

FEMTOLAND

1 fs=10^{-15} s

CORKUM -
the duration of this light pulse “is to a minute as a minute is to the age of the universe

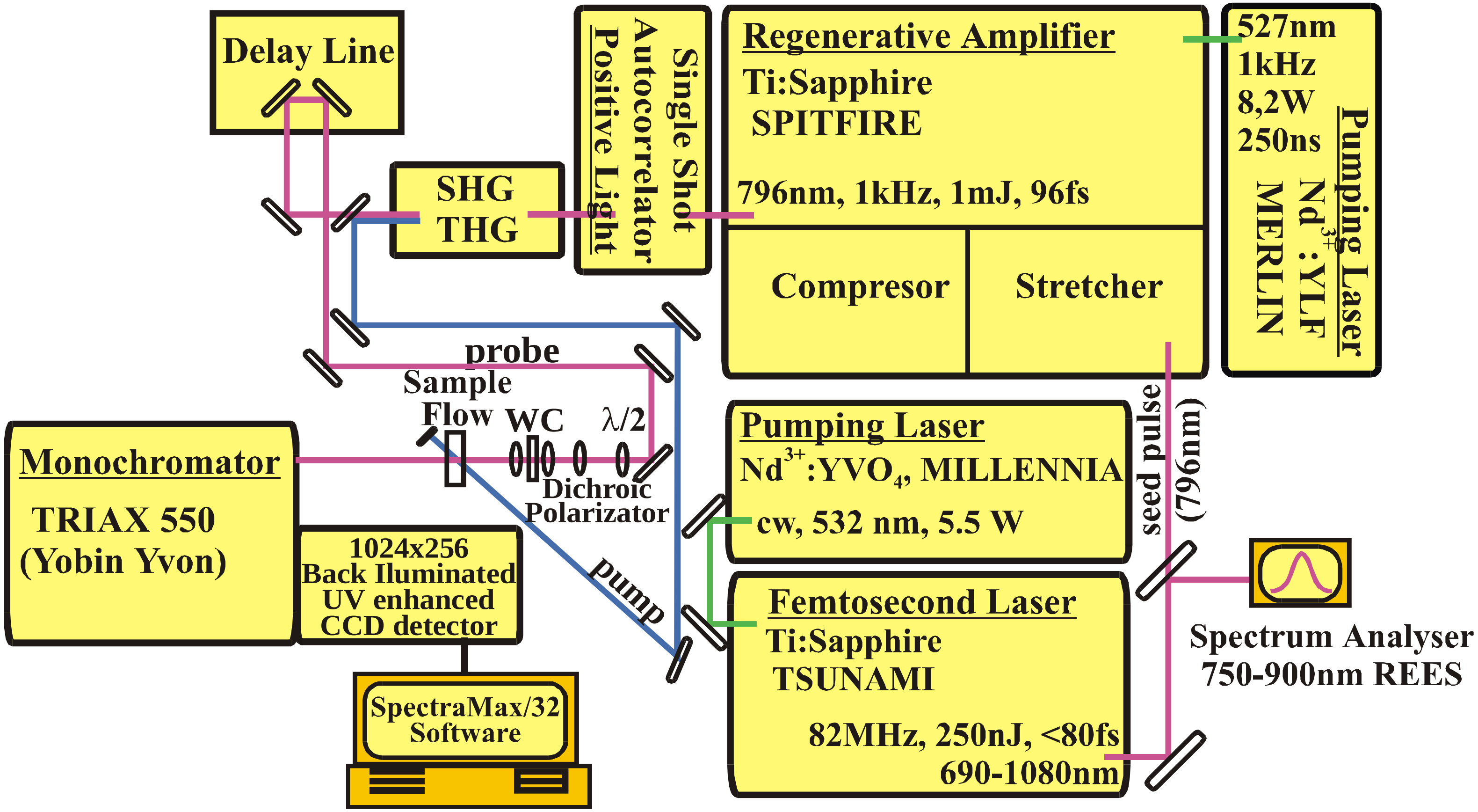
TREBINO -
the duration of this light pulse “is to a second as a 5 cents to the US national debt



Small but mighty—the power of concentration

Parameters
peak power – 0.12 MW ; electric power station EC-2 00 MW
peak power after amplification – **10 GW ; electric power station in Polish Bełchatów** 4 GW
power density – 10^{8} W/cm²
after amplification - 10^{11} W/cm²

pump-probe femtosecond UV/VIS/NIR absorption



Delay Line

SHG
THG

Single Shot Autocorrelator Positive Light

Regenerative Amplifier
Ti:Sapphire
SPITFIRE
796nm, 1kHz, 1mJ, 96fs

Compresor

Stretcher

527nm
1kHz
8,2W
250ns
Pumping Laser
Nd^{3+}:YLF
MERLIN

probe

Sample Flow

WC

λ/2

Dichroic
Polarizator

pump

Monochromator
TRIAX 550
(Yobin Yvon)

1024x256
Back Iluminated
UV enhanced
CCD detector

SpectraMax/32
Software

Pumping Laser
Nd^{3+}:YVO_4, MILLENNIA
cw, 532 nm, 5.5 W

Femtosecond Laser
Ti:Sapphire
TSUNAMI
82MHz, 250nJ, <80fs
690-1080nm

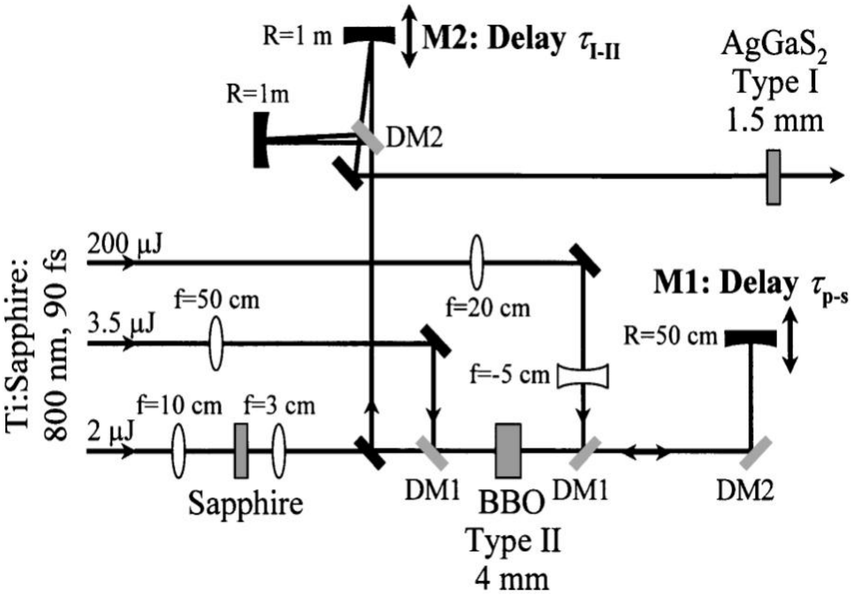
seed pulse
(796nm)

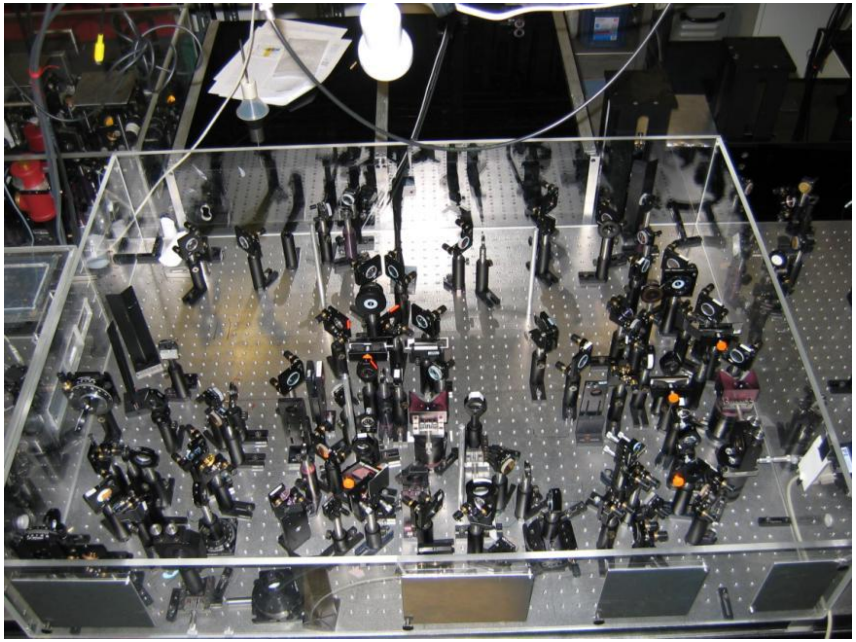
Spectrum Analyser
750-900nm REES

Femtosecond infrared pump-probe absorption

- Population relaxation,vibrational lifetime T1
- Energy transfer between modes
- Anizotropy of polarization

2.5-6 μm,
130 fs,
1-2 μJ

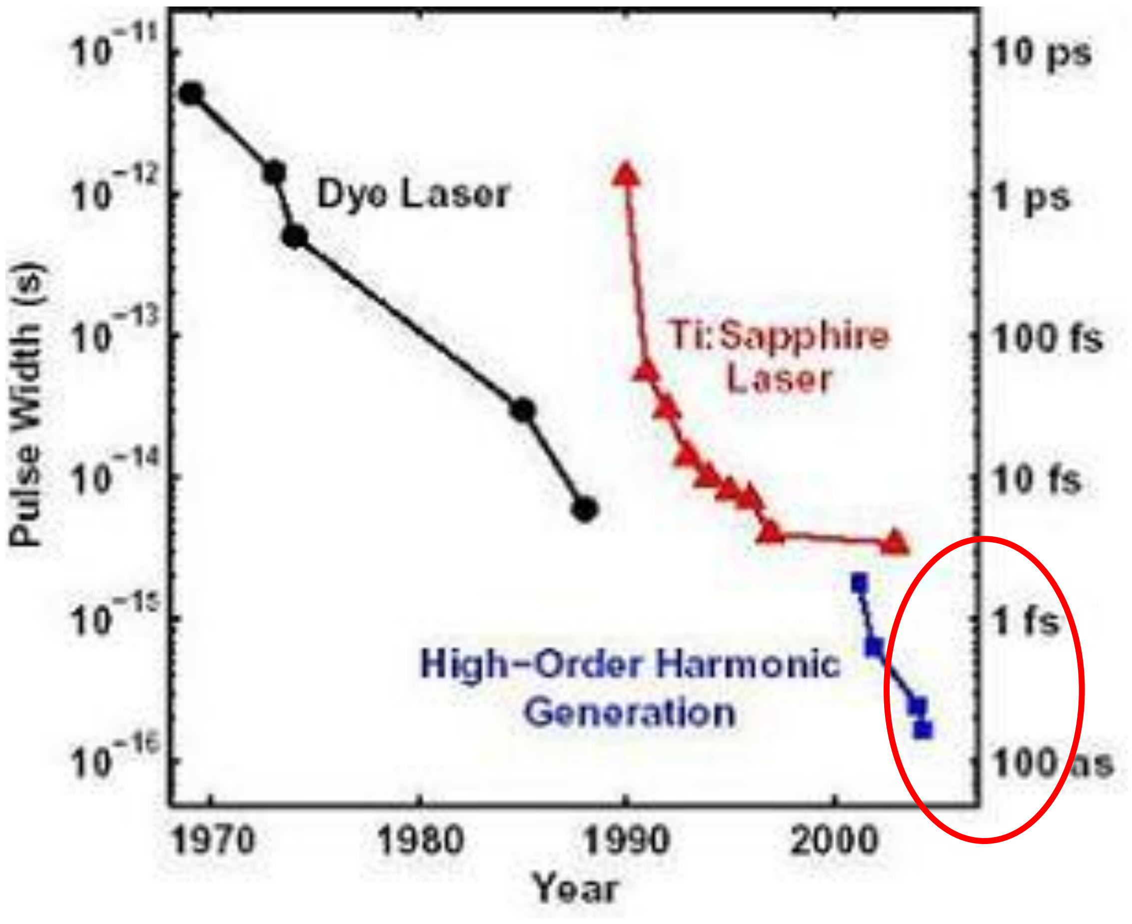




Max Born Institute , C, Berlin, Germany

P. Hamm *et al.*, Opt. Lett. (2000) **25**, 1798.
R.A. Kaindl *et al.*, J Opt. Soc. Am. B. (2000) **17**, 2086.

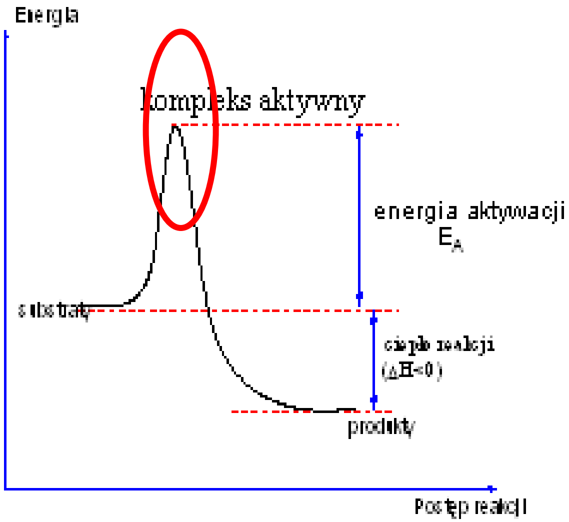
In 2001 the femtosecond barrier has been broken by going into extreme ultraviolet range and by using high-order harmonic generation in gases



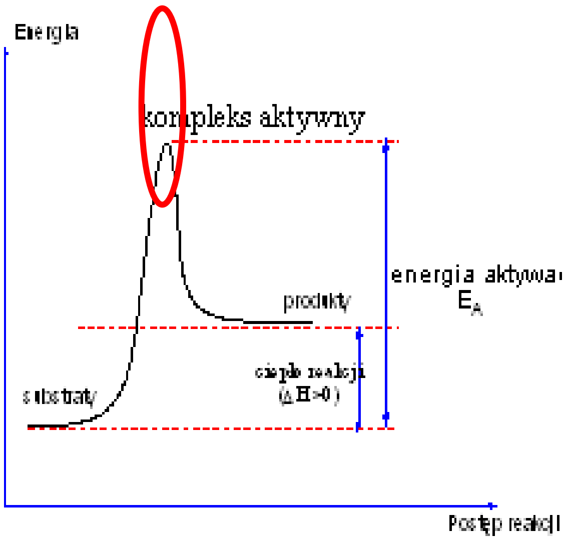
What can we do with something so infinitesimally short?

photographing chemical reactions

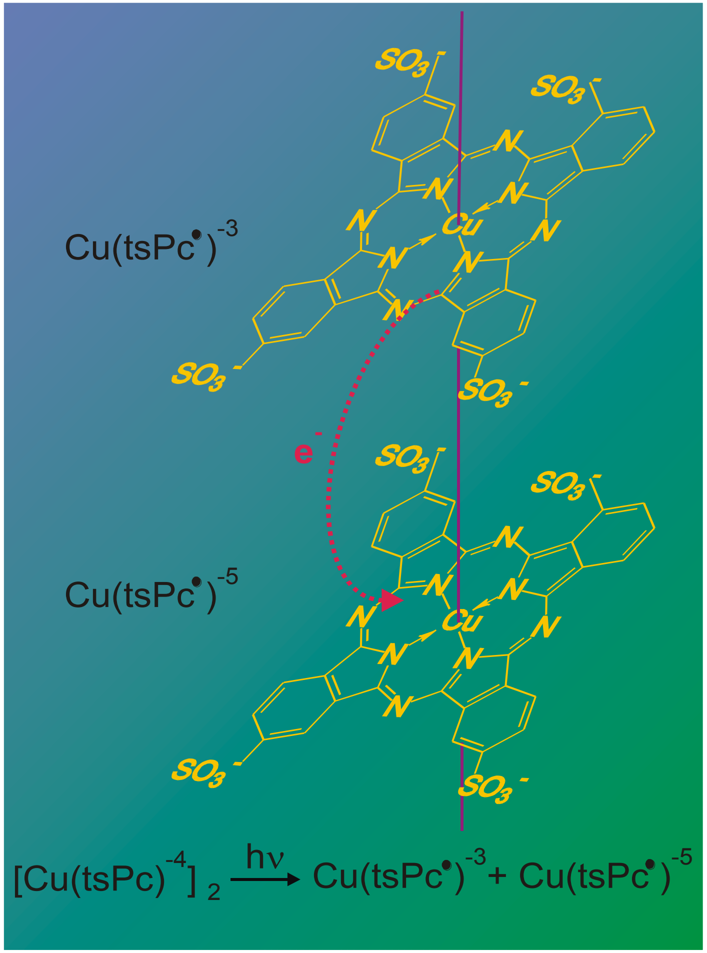
Reakcja egzotermiczna



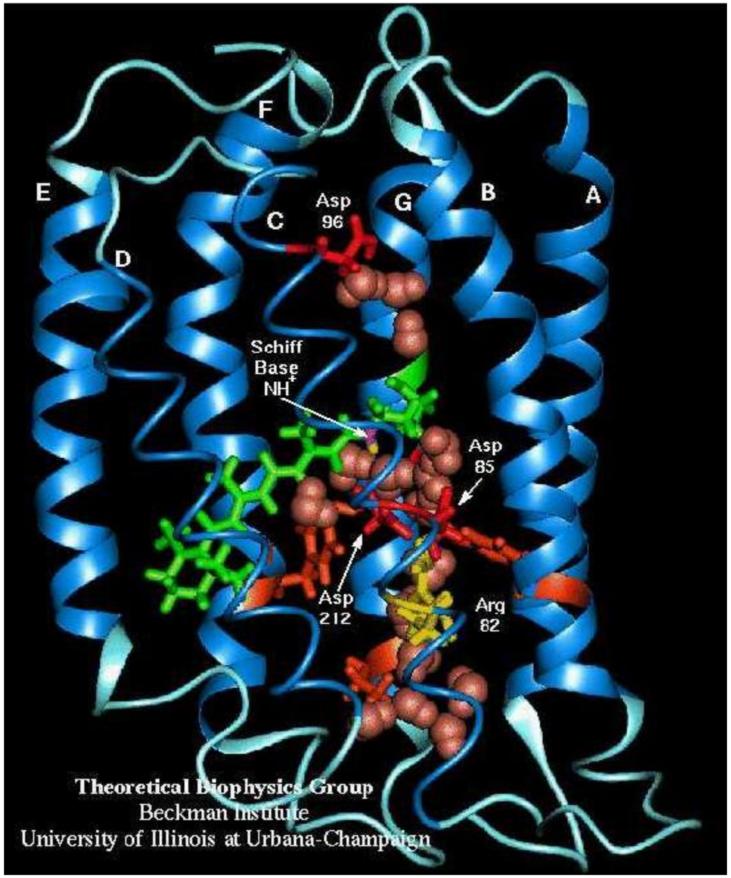
Reakcja endotermiczna



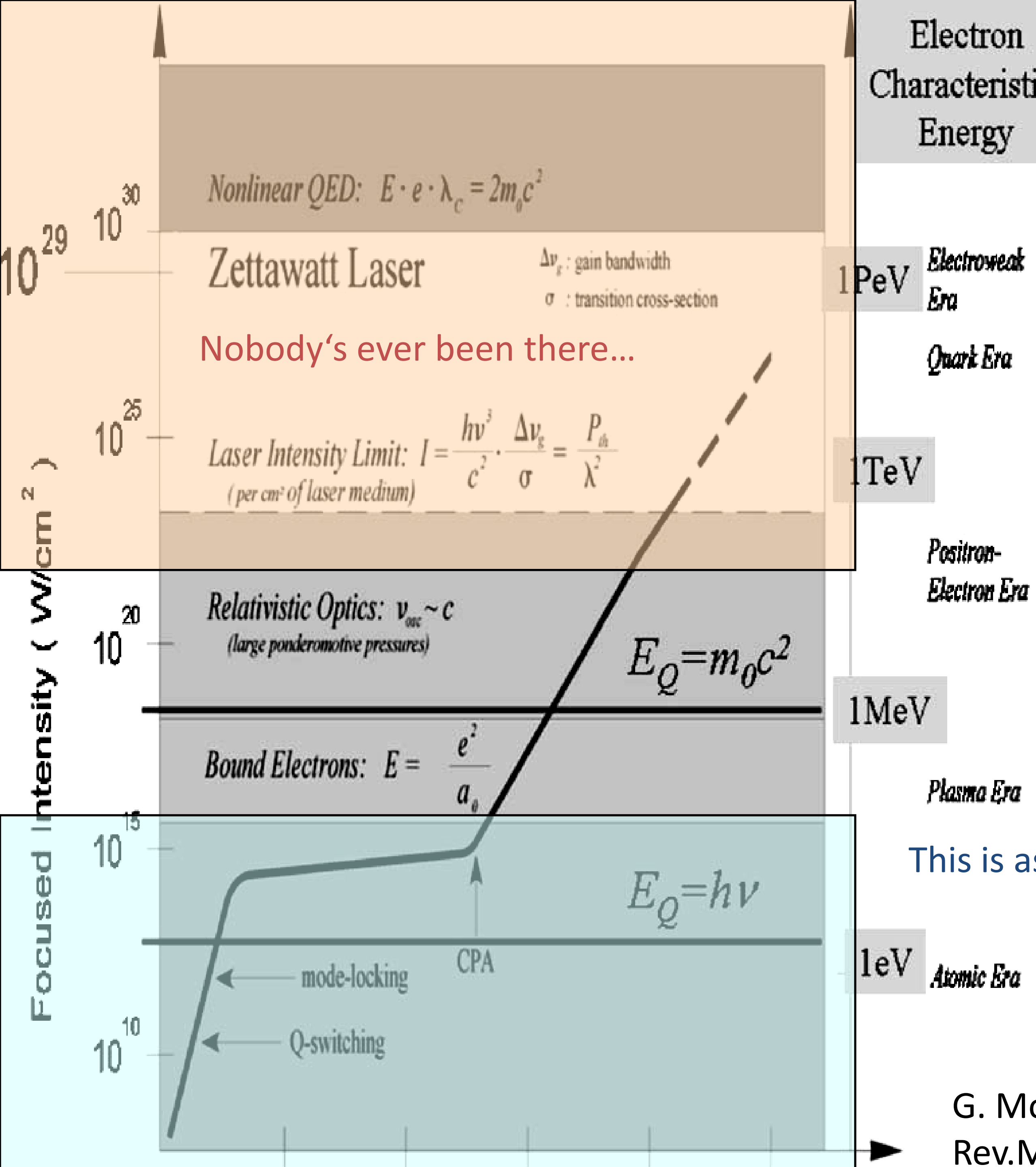
Ultrafast processes of photosentisitizers in photodynamic therapy of cancer – metal complexes of phthalocyanines and bacteriorhodopsin



$$[\mathrm{Cu(tsPc)}^{-4}]_2 \xrightarrow{h\nu} \mathrm{Cu(tsPc^{\bullet})}^{-3} + \mathrm{Cu(tsPc^{\bullet})}^{-5}$$



Theoretical Biophysics Group
Beckman Institute
University of Illinois at Urbana-Champaign



Nobody‘s ever been there…

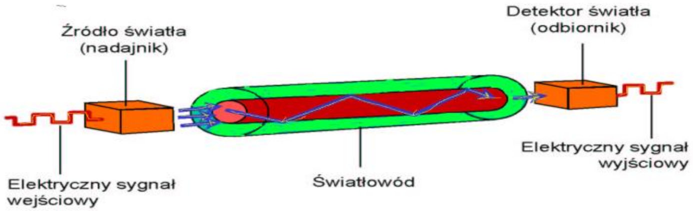
The advent of ultraintense laser pulses generated by the technique of chirped pulse amplification (CPA) along with the development of high-fluence laser materials has opened up an entirely new field of optics. The electromagnetic field intensities produced by these techniques, in excess of 10^{18} W/cm², lead to relativistic electron motion in the laser field. In contrast to the nonrelativistic regime, these laser fields are capable of moving matter more effectively, including motion in the direction of laser propagation. One of the consequences of this is wakefield generation, a relativistic version of optical rectification, in which longitudinal field effects could be as large as the transverse ones. In addition to this, other effects may occur, including relativistic focusing, relativistic transparency, nonlinear modulation and multiple harmonic generation, and strong coupling to matter and other fields (such as high-frequency radiation). A proper utilization of these phenomena and effects leads to the new technology of relativistic engineering, in which light-matter interactions in the relativistic regime drives the development of laser-driven accelerator science. A number of significant applications are reviewed, including the fast ignition of an inertially confined fusion target by short-pulsed laser energy and potential sources of energetic particles (electrons, protons, other ions, positrons, pions, etc.). The coupling of an intense laser field to matter also has implications for the study of the highest energies in astrophysics, such as ultrahigh-energy cosmic rays, with energies in excess of 10^{20} eV. The laser fields can be so intense as to make the accelerating field large enough for general relativistic effects (via the equivalence principle) to be examined in the laboratory. It will also enable one to access the nonlinear regime of quantum electrodynamics, where the effects of radiative damping are no longer negligible. Furthermore, when the fields are close to the Schwinger value, the vacuum can behave like a nonlinear medium in much the same way as ordinary dielectric matter expanded to laser radiation in the early days of laser research

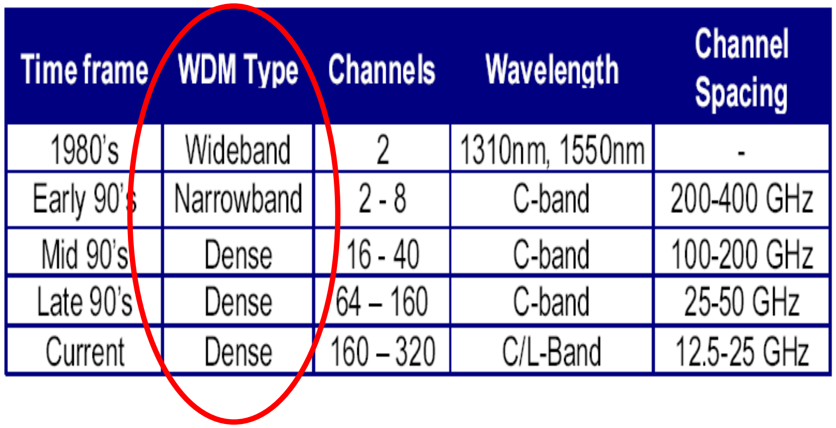
This is as far as I will take you…

G. Mourou et al.
Rev.Mod.Phys. 78, 309 (2006).

Such a OPCPA system could maintain tens of femtosecond pulse duration of an OPA system, while increasing pulse energies well above the Joule leading to focused intensities of 10^{24} W/cm^2 or higher. Such intensities are enormously high. Indeed, only 10^{15} W/cm^2 is required to ionize nearly all the material, at 10^{18} W/cm^2 electrons can be accelerated to nearly the speed of light. As a result of such a high intensity light pressure exceeds the thermal pressure generating extremely dense plasma with multikiloelectronovolts energy. At such high densities, energies and pressures, interaction of electrons with plasma ions generates extremely short X-ray pulses. Moreover, difference in speed of light electrons and heavy ions produces a plasma wave that induces fields of 100 GeV/m much higher than available in conventional today’s accelerators. Going to more powerful pulses, self-focusing of the pulse occurs leading to intensities of 10^{20} W/cm^2 that can ignite a pellet of fusion fuel

What can we do with so infinitesimally short pulses in real world applications?

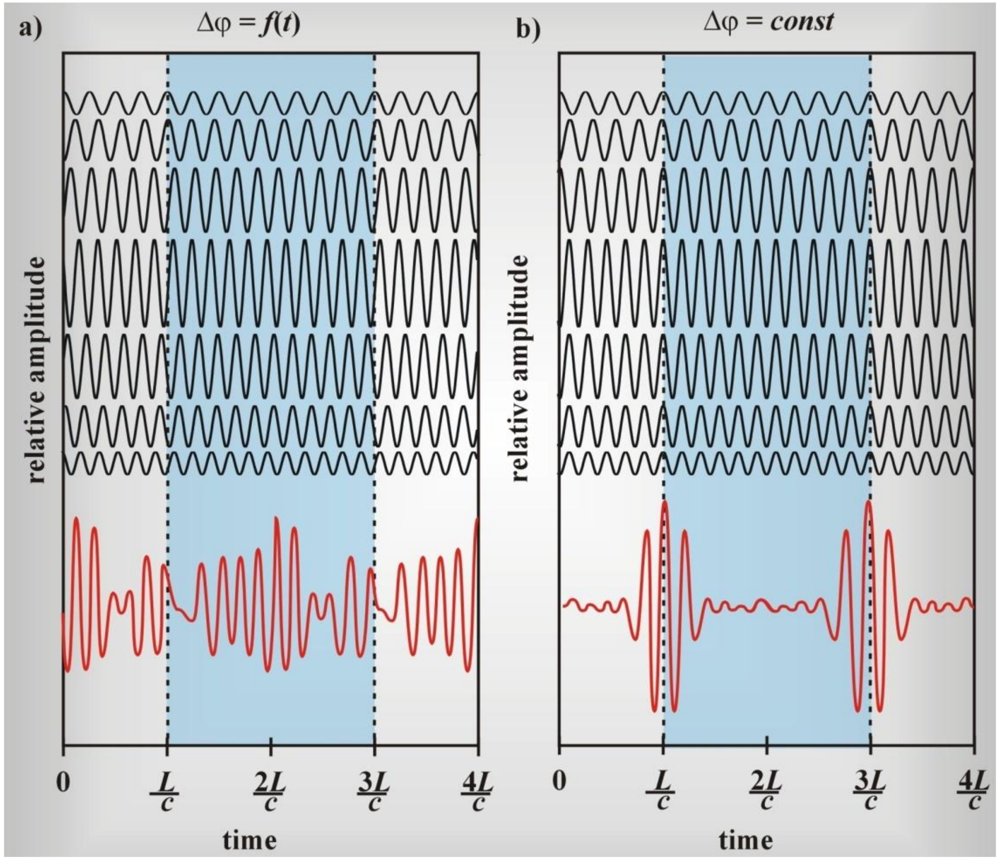




Time frame	WDM Type	Channels	Wavelength	Channel Spacing
1980's	Wideband	2	1310nm, 1550nm	-
Early 90's	Narrowband	2 - 8	C-band	200-400 GHz
Mid 90's	Dense	16 - 40	C-band	100-200 GHz
Late 90's	Dense	64 – 160	C-band	25-50 GHz
Current	Dense	160 – 320	C/L-Band	12.5-25 GHz

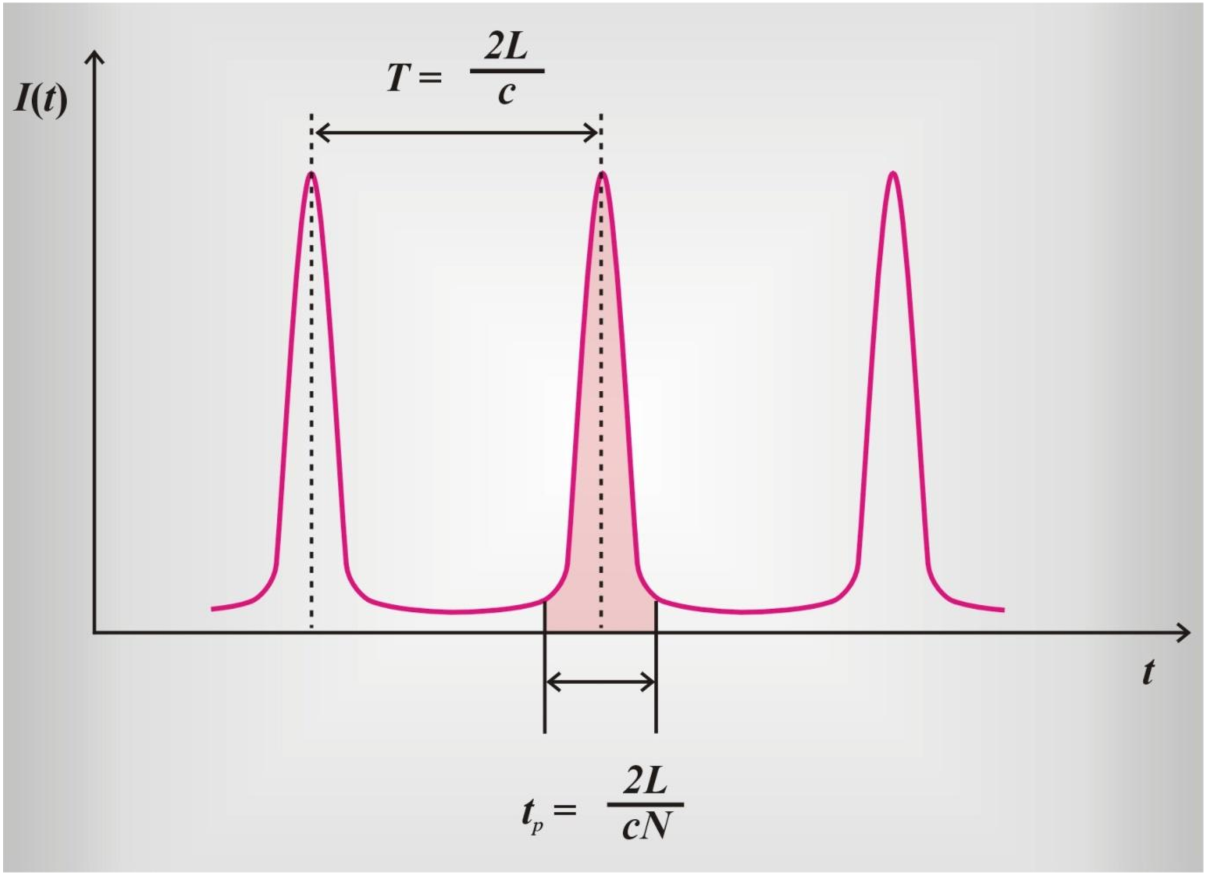
- Fast optical networks utilizing the wavelength multiplexing technologies WDM, DWDM, UWDM are one of the greatest beneficient of the modern laser technology in building of complete optical platforms that includes
- optical fibers
- lasers, modulators, reflectometers
- optical amplifiers
- multiplexers and demultiplexers
- switches and teracommutators

In a free-running regime discussed so far lasers produce a mixture of transverse and longitudinal modes with random mode-to-mode phase relationship that changes with time. It is not surprising because coherence is only a single mode feature. Each mode oscillates independently of the others modes. The intensity of the signal in the free multimode regime that results from the interference of longitudinal modes with random phase relations is a chaotic sequence of fluctuations that looks like the characteristics of thermal noises



Suppose that it is possible to achieve a situation when the phases of the longitudinal modes are forced to maintain a fixed phase relationship to each other. Such a laser is said to be *modelocked* or *phase-locked*. How to achieve it is another story and we will discuss this issue later.

The modelocking results in a train of pulses with the repetition period *T* equal to the round-trip time in the optical resonator and the pulse temporal duration t_p equal to the round-trip time divided a number of phase locked modes *N*.



- In this case the laser output shows a periodic repetition of a wave packet resulting from the constructive interference of longitudinal modes (fig. 3.1b). The sequence of regular pulses occurs with the period $T = 2L/c$

whereas the single pulse temporal duration t_p is given by $t_p = \frac{T}{N} = \frac{2L}{cN}$

where *N* is a number of modes generated in an optical resonator (fig. 3.2), *L* – length of resonator, *c* – the speed of the light

Let assume that the electric field is represented by N plane waves

$$E(t) = E_0 e^{i\omega t}$$

$$N = 2n + 1$$

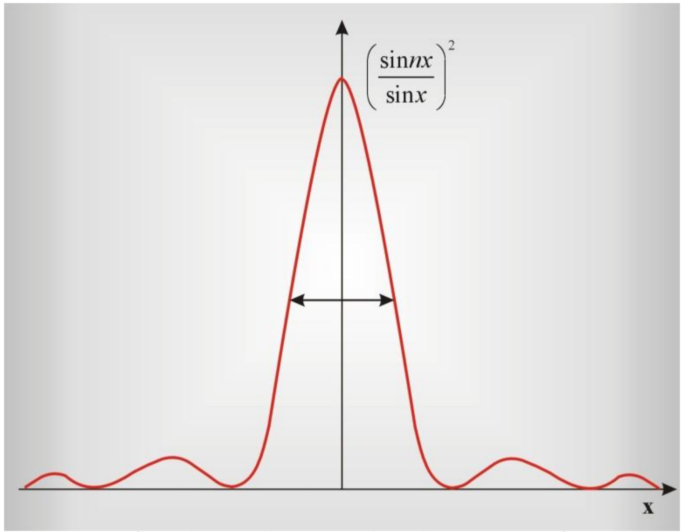
The total electric field of N modes is

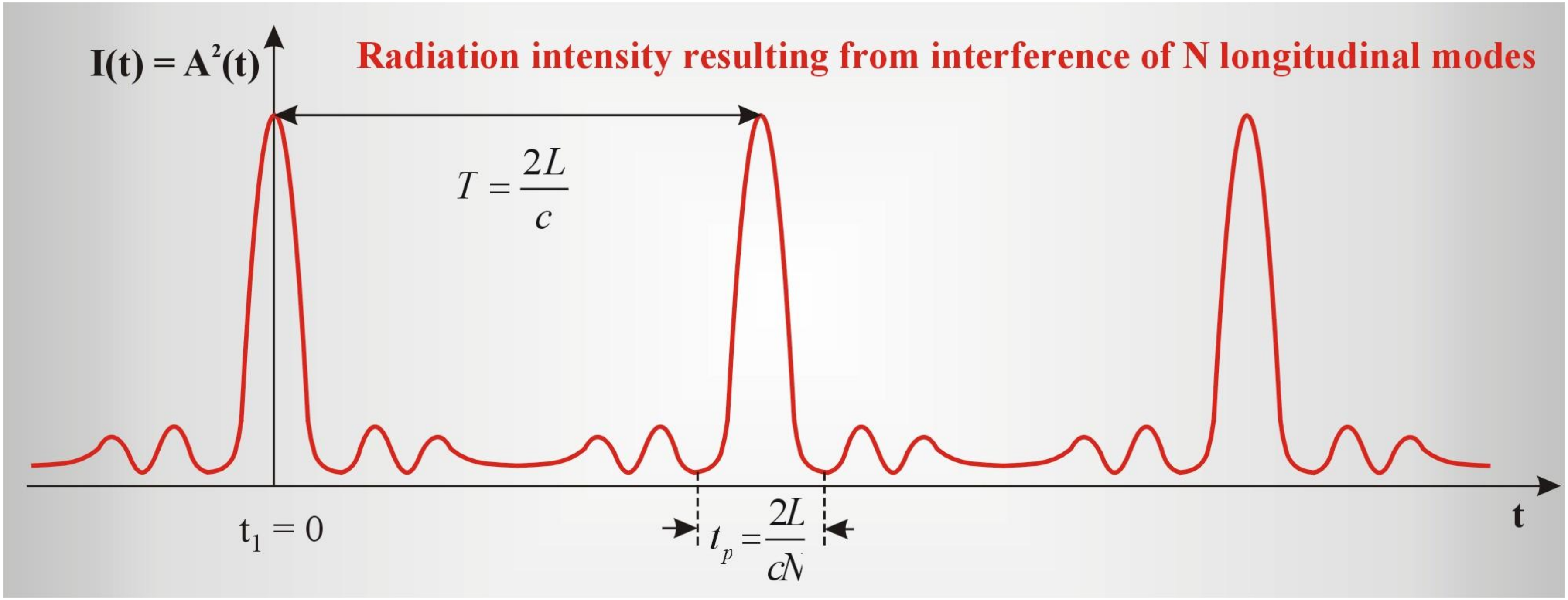
$$E(t) = \sum_{k=-n}^{n} E_0 \exp i\left[\left(\omega_0 + k\Delta\omega_q\right)t + k\Delta\varphi_q\right]$$

a. When $\Delta\varphi_q = \Delta\varphi_q(t)$ **one get chaotic mixture of modes**

b. **when** $\Delta\varphi_q = const$ **one can show that the total electric field is**

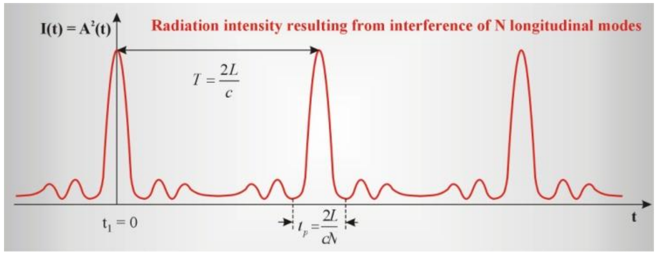
$$E(t) = E_0 \exp(i\omega_0 t)\frac{\sin\left[\frac{N\left(\Delta\omega_q t + \Delta\varphi_q\right)}{2}\right]}{\sin\left(\frac{\Delta\omega_q t + \Delta\varphi_q}{2}\right)}$$





Radiation intensity resulting from interference of N longitudinal modes

Let calculate the period of repetition T



$$\frac{\partial E}{\partial t} = 0 \Rightarrow \left(\frac{\sin(N\alpha/2)}{\sin(\alpha/2)} \right)' = \frac{\cos(N\alpha/2)N/2}{\sin(\alpha/2)} + $$

$$- \frac{\sin(N\alpha/2)\cdot\cos(\alpha/2)}{\sin^2(\alpha/2)} \cdot \frac{1}{2} = 0$$

$$\Rightarrow \frac{N}{2}\cos\frac{N\alpha}{2} = \frac{1}{2}\frac{\sin(N\alpha/2)}{\sin(\alpha/2)}\cdot\cos(\alpha/2) \Rightarrow$$

$$Ntg\frac{\alpha}{2} = tg\frac{N\alpha}{2} \Rightarrow tg\frac{\alpha}{2} = 0$$

$$\alpha_1 = \left(\Delta\omega_q t_1 + \Delta\varphi_q\right)/2 = 0$$

$$\alpha_2 = \left(\Delta\omega_q t_2 + \Delta\varphi_q\right)/2 = \pi$$

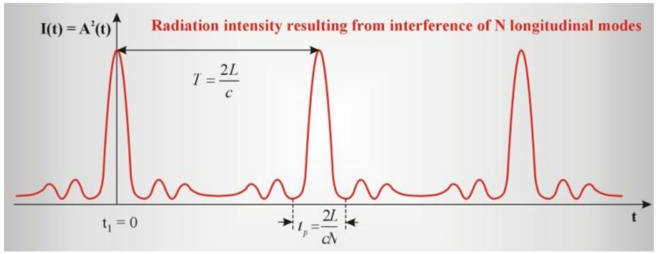
$$\left\{ \begin{aligned} T &= t_2 - t_1 = \\ &= \frac{2\pi}{\Delta\omega_q} = \\ &= \frac{2\pi}{2\pi(c/2L)} = \\ &= \frac{2L}{c} \end{aligned} \right.$$

Duration of a single pulse is $t_p = 2L/Nc$

$$\sin N\left(\Delta\omega_q t + \Delta\varphi_q\right)/2 = 0 \Rightarrow$$

$$\left.\begin{aligned} N\left(\Delta\omega_q t_1 + \Delta\varphi_q\right)/2 &= 0 \\ N\left(\Delta\omega_q t_2 + \Delta\varphi_q\right)/2 &= \pi \end{aligned}\right\} \Rightarrow t_2 - t_1 =$$

$$\frac{2\pi}{N\Delta\omega_q} = \frac{2L}{Nc}$$



Perfect modelocking

The magnitude of the product $\Delta t \cdot \Delta E$

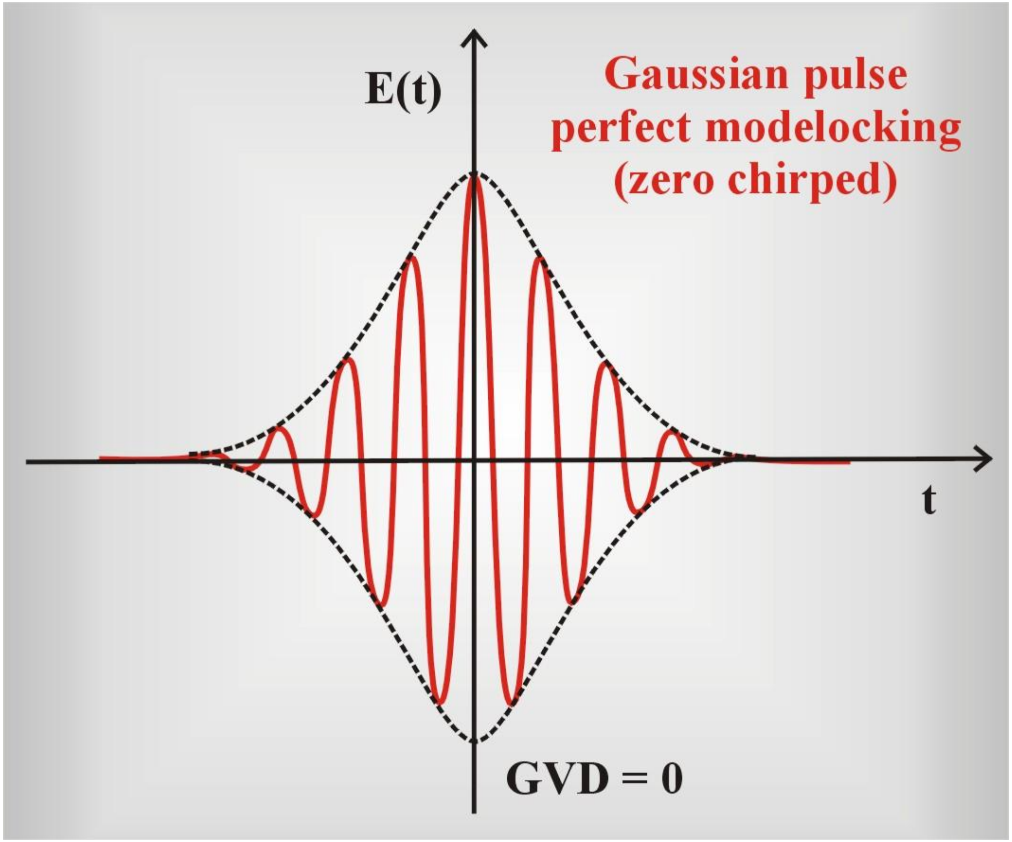
depends on a temporary pulse shape.
Assume that the temporary pulse shape is described by a Gaussian function

$$E(t) = \frac{E_0}{\tau} \exp\left(-\frac{t^2}{2\tau^2} \right)$$

The frequency spectrum $E(\omega)$

can be obtained from the Fourier transform

$$E(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E(t)\, e^{-i\omega t} dt = \frac{E_0}{2\pi} \exp\left[-\frac{\tau^2}{2} (\omega - \omega_0)^2 \right]$$



Thus, for the Gaussian profile the product $\Delta t \cdot \Delta E$ is equal to $\Delta t_{FWHH} \cdot \Delta \nu_{FWHH} = 0.441$

The relation derived in eq. corresponds to an ideal situation of a perfectly modelocked laser with a pulse called the *Fourier-transform limited pulse*.
Such a pulse is the shortest pulse Δt_{FWHH}
that can be generated for a given gain spectrum $\Delta \nu_{\mathrm{FWHH}}$

In practice such pulses are seldom produced.

- The uncertainty relation holds only when the individual longitudinal modes are perfectly synchronized with each other, or in other words, when the spectral phase is a linear function of frequency

$$E(\omega) = A(\omega)e^{i\Phi(\omega)}$$
$$\Phi(\omega) = \Phi_0 + \Phi_1(\omega - \omega_0)$$

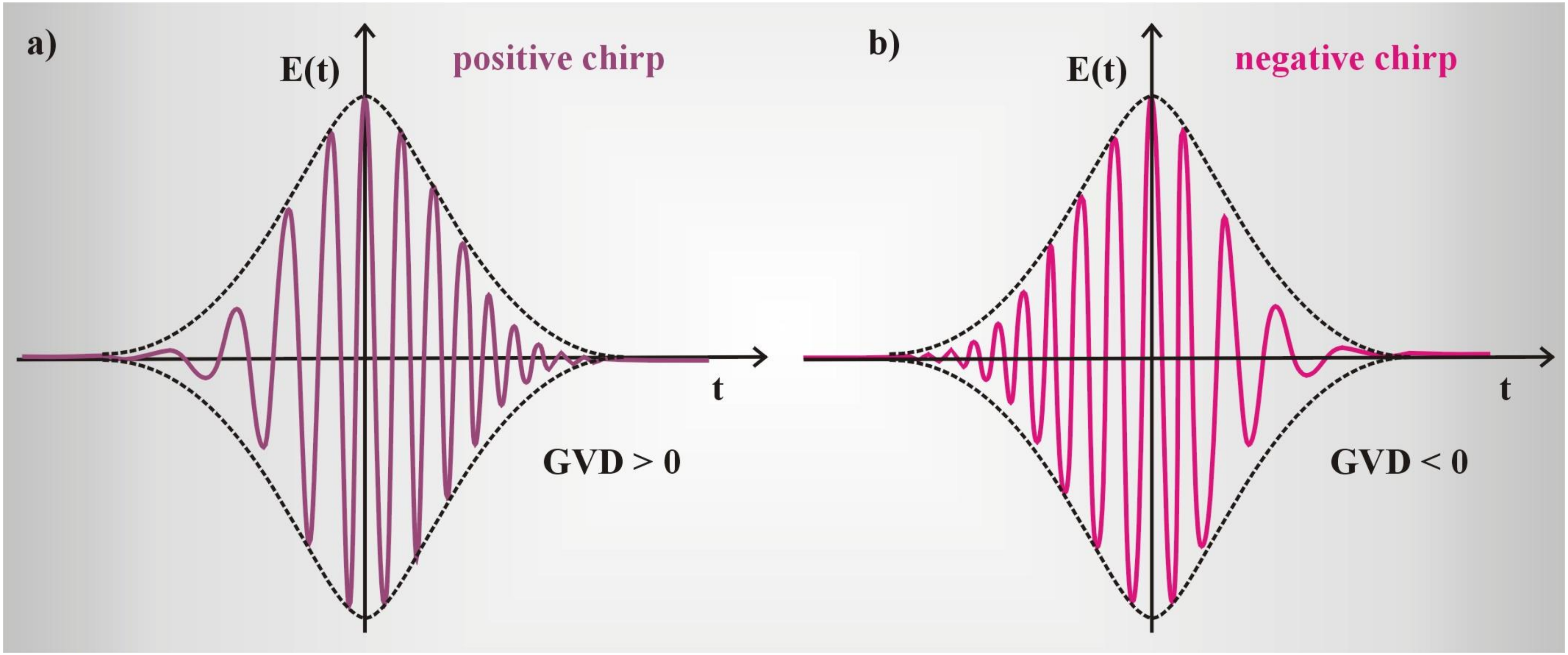
It is crucial for perfect modelocking that all frequency components experience the same round-trip cavity time which is ensured by the phase linearity . Due to material dispersion each frequency component travels with different velocity (so called *group velocity*) and the spectral phase is usually more complicated than linear

$$\Phi(\omega) = \sum_0^{\infty} \frac{1}{n!} \left.\frac{d^n\phi}{d\omega^n}\right|_{\omega_0} (\omega - \omega_0)^n$$

Due to the quadratic term in phase each frequency component that comprises the spectrum of the pulse experiences the delay linearly proportional to the offset from the central frequency ω_0

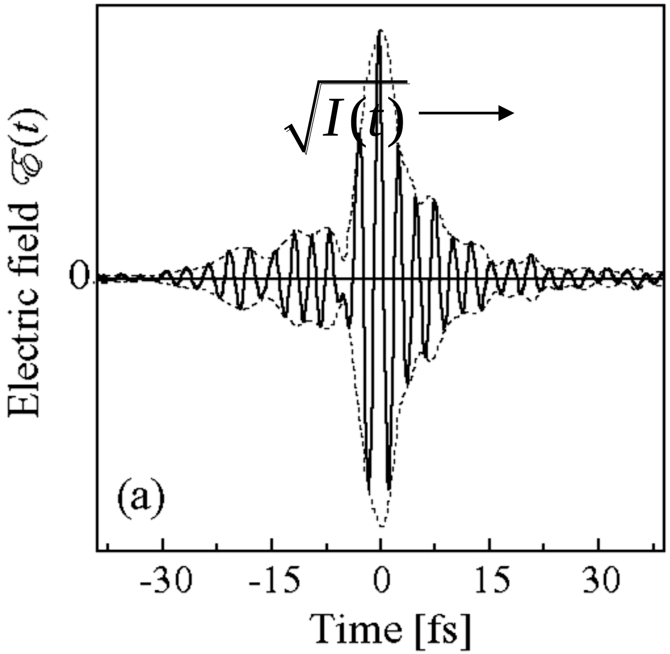
The pulse is said to be *linearly chirped*. In this case, a Gaussian pulse for an ideal modelocking is replaced by a Gaussian pulse linearly chirped (fig. 3.7). The linear chirp can be negative or positive . For the positive chirp red components travel faster than blue ones in contrast to the negative chirp.

Real world (dispersion)



To produce pulses as short as possible, dispersion in the cavity must be compensated for by adding optical elements – typically pairs of prisms or gratings, specially coated mirrors or a length of optical fiber

A light wave has intensity and phase vs. time.



Neglecting the spatial dependence for now, the pulse electric field is given by:

$$E(t) = \mathrm{Re}\left\{ \sqrt{I(t)}\, \exp\{i[\omega_0 t - \phi(t)]\} \right\}$$

Intensity

Carrier frequency

Phase

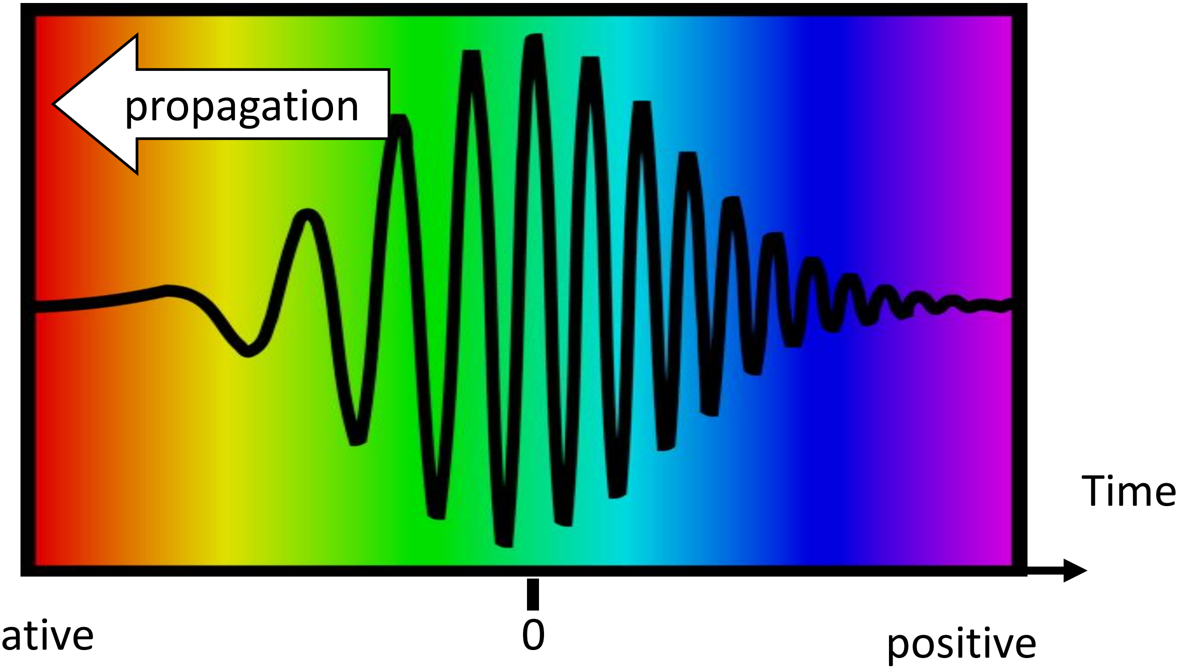
Slowly-varying envelope approximation, can be used down to about two optical cycles with some care.

The Chirp (Instantaneous frequency)

The temporal phase, $\phi(t)$, contains frequency-vs.-time information.

The pulse *instantaneous angular frequency*, $\omega_{inst}(t)$, is defined as:

$$\boxed{\omega_{inst}(t) \equiv \omega_0 - \frac{d\phi}{dt}}$$



This pulse increases its frequency linearly in time (from red to blue).

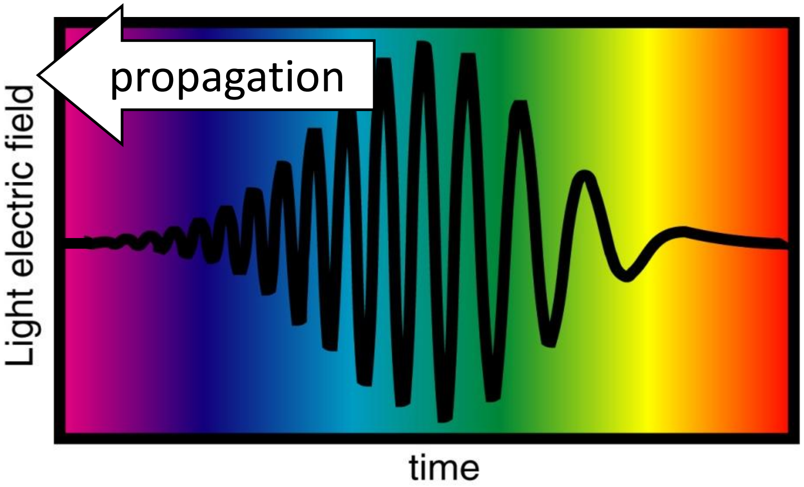
In analogy to bird sounds, this pulse is called a "chirped" pulse.
This pulse is positively chirped, i.e., red leading blue, as from material dispersion !

The Negatively Chirped Pulse

- We have been considering a pulse whose frequency *increases*
- linearly with time: a *positively* chirped pulse.

- One can also have a *negatively*
- chirped (Gaussian) pulse, whose
- instantaneous frequency
- *decreases* with time.

- We simply allow β to be *negative*
- in the expression for the pulse:



$$E(t) = \operatorname{Re} E_0 \exp\left[-(t/\tau_G)^2\right] \exp\left[i\left(\omega_0 t + \beta t^2\right)\right]$$

- And the instantaneous frequency will decrease with time:

$$\omega_{inst}(t) = \omega_0 + 2\beta t = \omega_0 - 2|\beta| t$$

Methods of mode-locking

Modulation of light with intramode frequency

$$\Delta\omega_q = \frac{c}{2L} \cdot 2\pi$$

a. active – external

- with electro-optic,
- acusto-optic devices

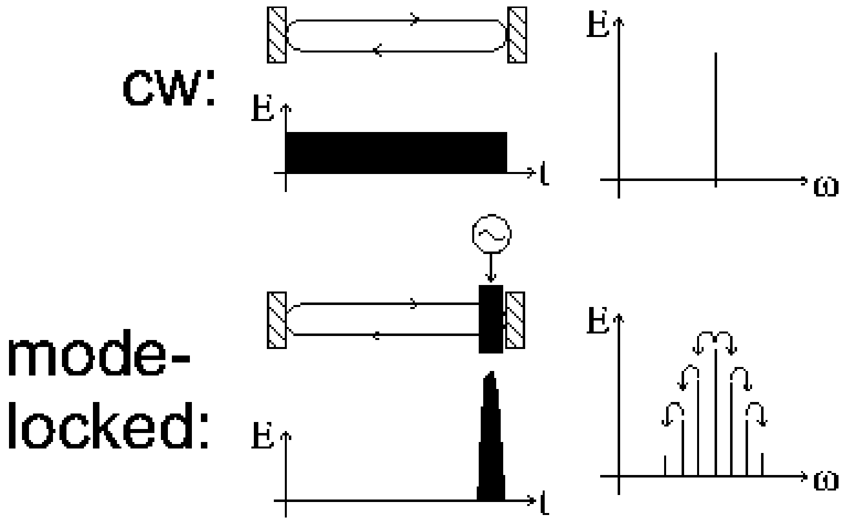
b. passive – automodelocking

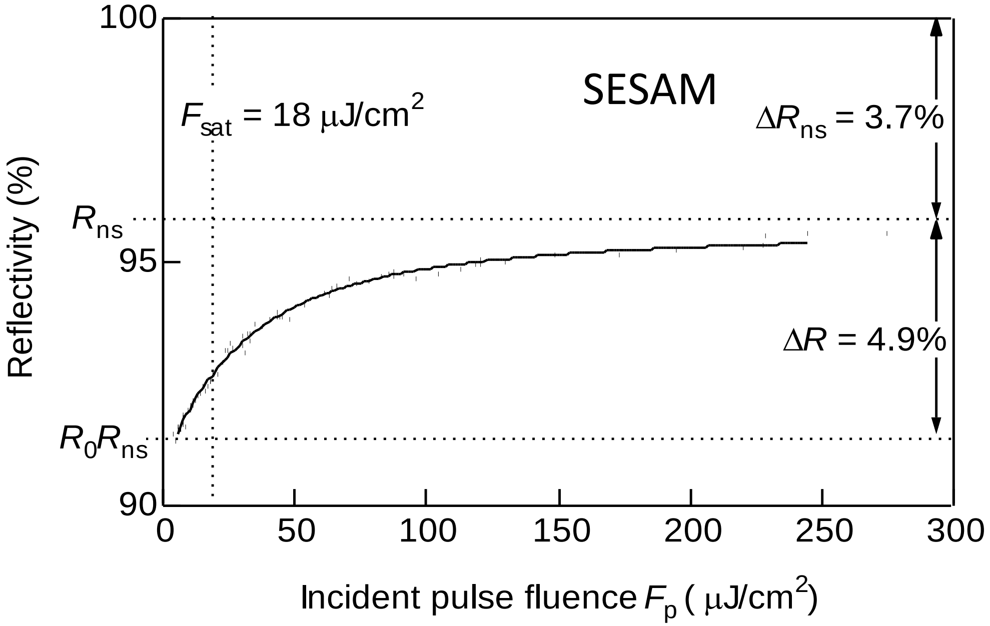
- Saturable absorbers (dyes, SESAM)
- Kerr self focusing lens)

Passive vs. active mode-locking

Active mode-locking:

Drive modulator with rf wave; generated sidebands coinciding with optical cavity modes





Passive mode-locking:

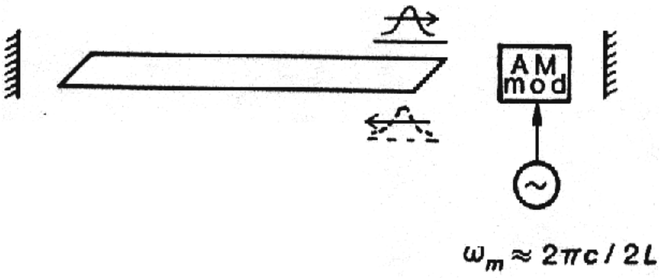
Use nonlinear transmission characteristics of a saturable absorber.
Pulse modulates its own transmision

G. Steinmeyer, European Virtual University, http://mitr.p.lodz.pl

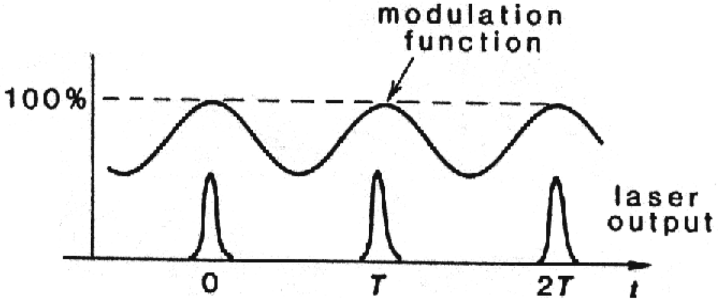
Mode-locking

- Intracavity optical switch opens and closes synchronously with the propagating optical pulse

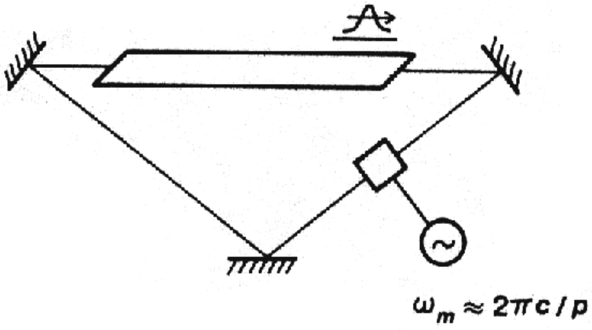
standing-wave cavity:



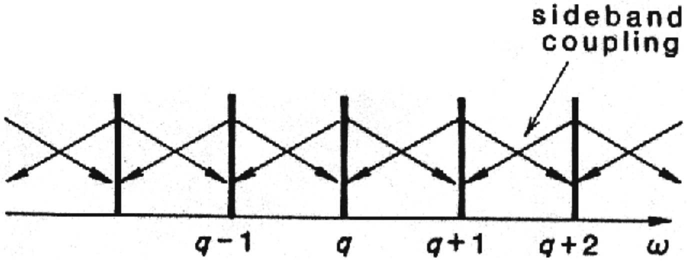
mode-locked time behavior:



ring laser cavity:



mode-locked frequency behavior:



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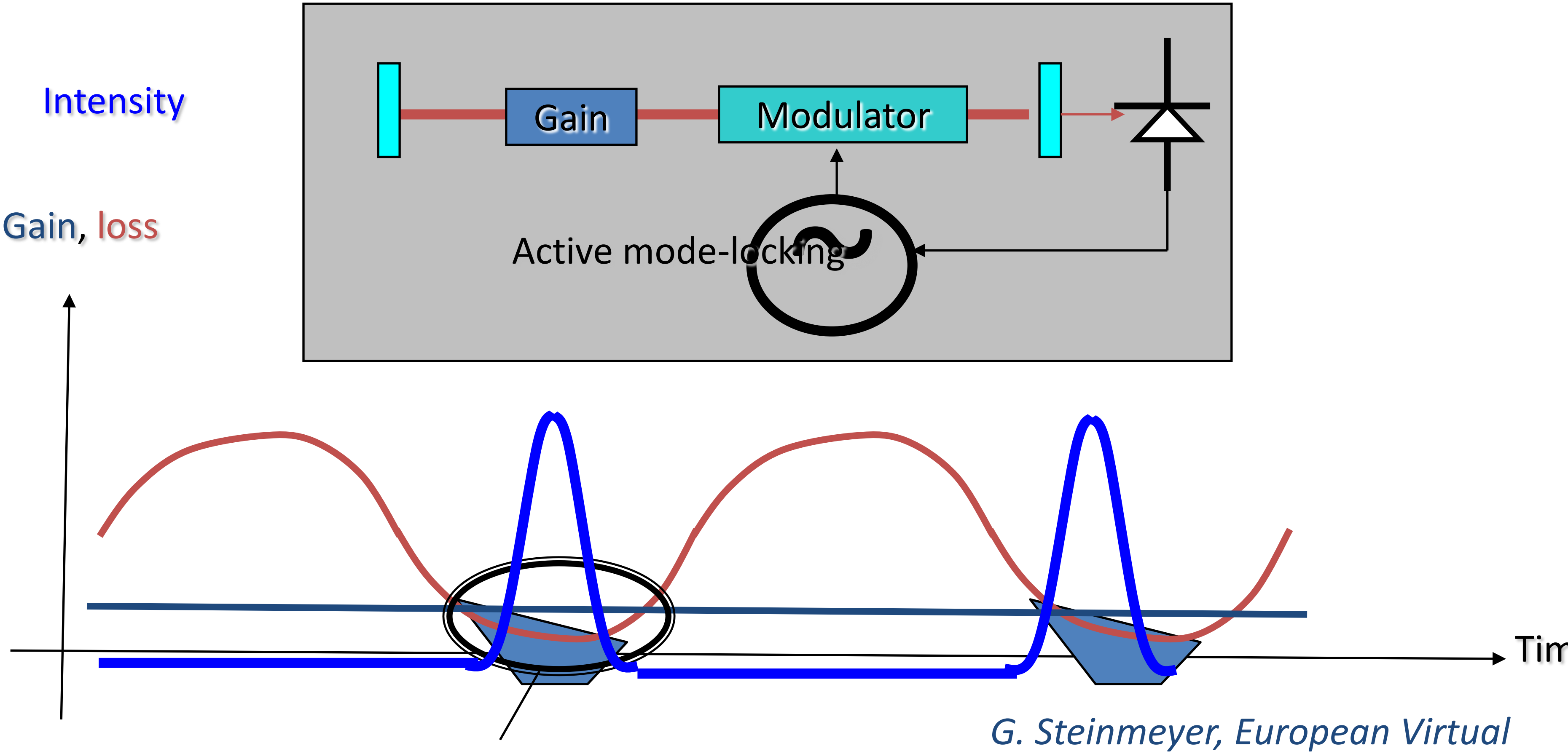
Net Gain Window (active mode-locking)



Net gain only here !

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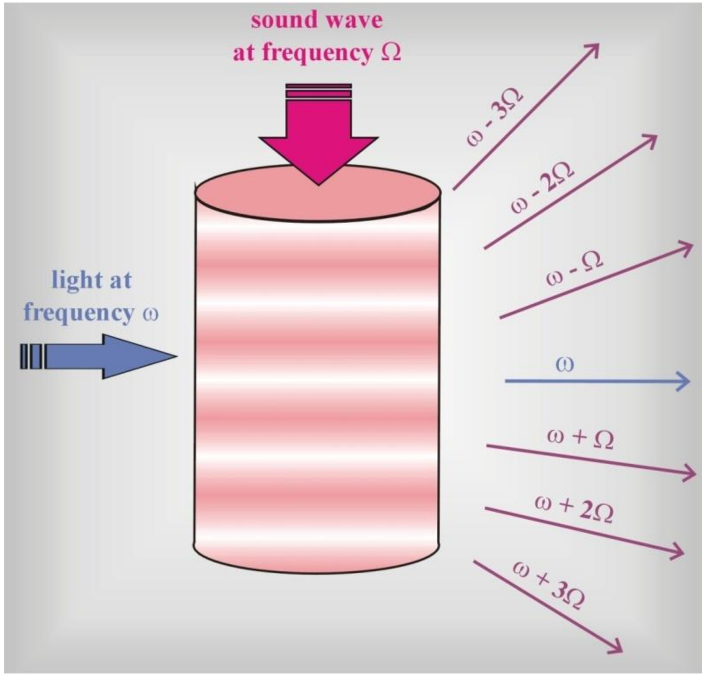
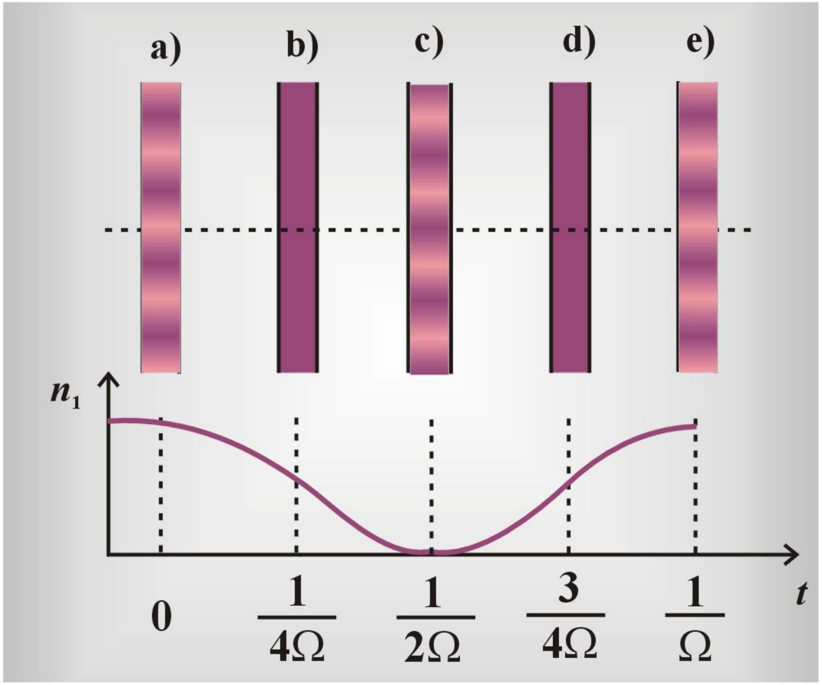
Modulation of light – idea of acousto-optic devices

The radio-frequency (RF) driver generates the acoustical wave in the transducer that propagates through the medium. The laser beam in the resonator interacts with the sound wave leading to diffraction of the incident beam.

The simplest way of modulation of the refraction index n_1 is a periodic change of a medium density, which can be achieved by passing the acoustic wave through the medium. The acoustic wave creates in the medium regions of compression and dilation at the acoustic wave frequency Ω



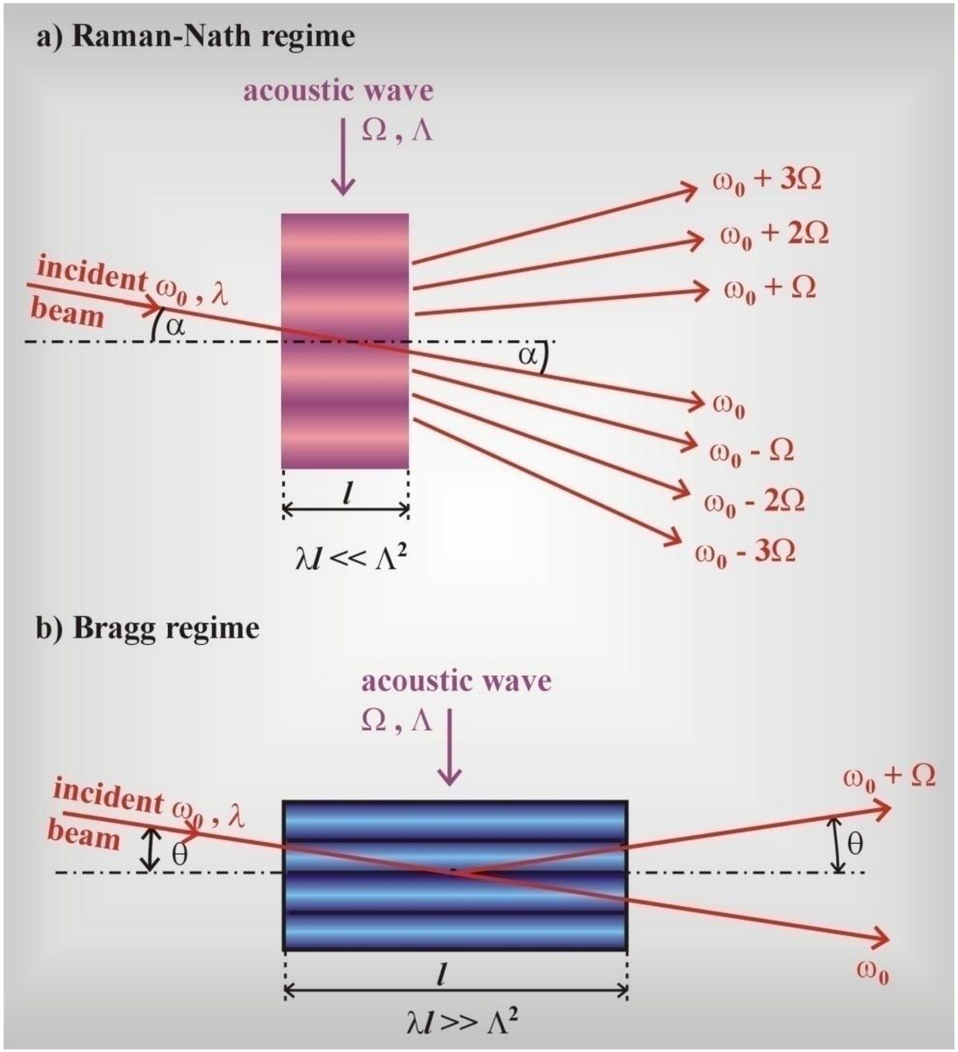


Twice during the cycle the density is distributed uniformly along the whole column (b and d) and twice it achieves maximum at which the refraction coefficient

is the largest (a and e) as well as once achieves the minimum density at which the refraction coefficient is the smallest

Debye and Sears effect

Raman-Nath regime
Bragg regime



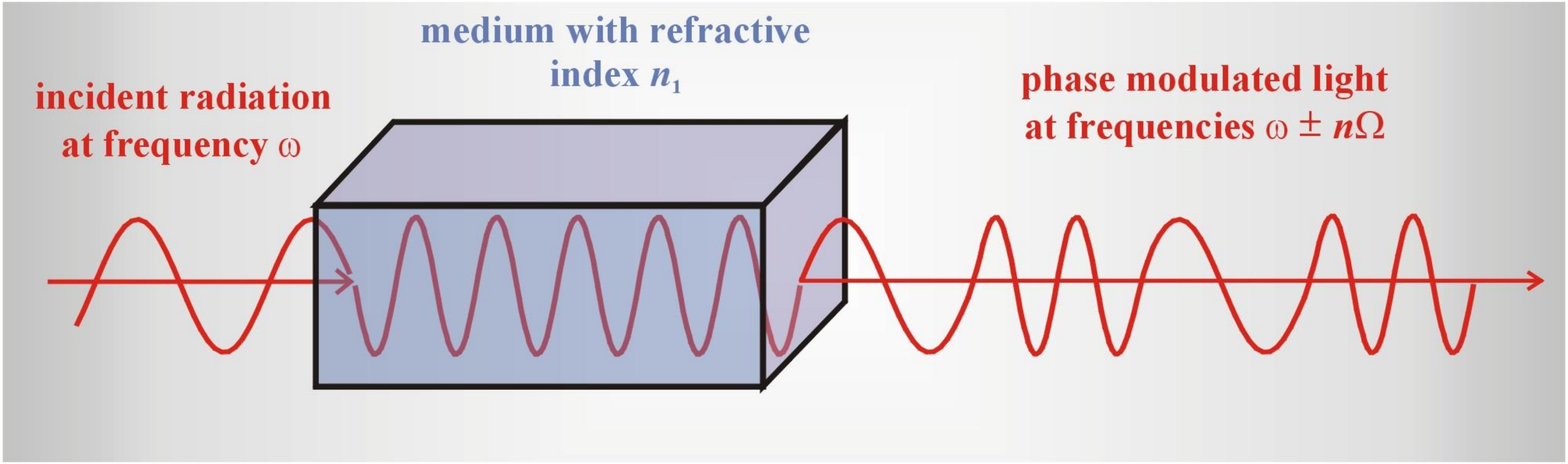
$$l << \frac{\Lambda^2}{2\pi\lambda}$$

Raman-Nath
regime-
modelocking

$$l >> \frac{\Lambda^2}{2\pi\lambda}$$

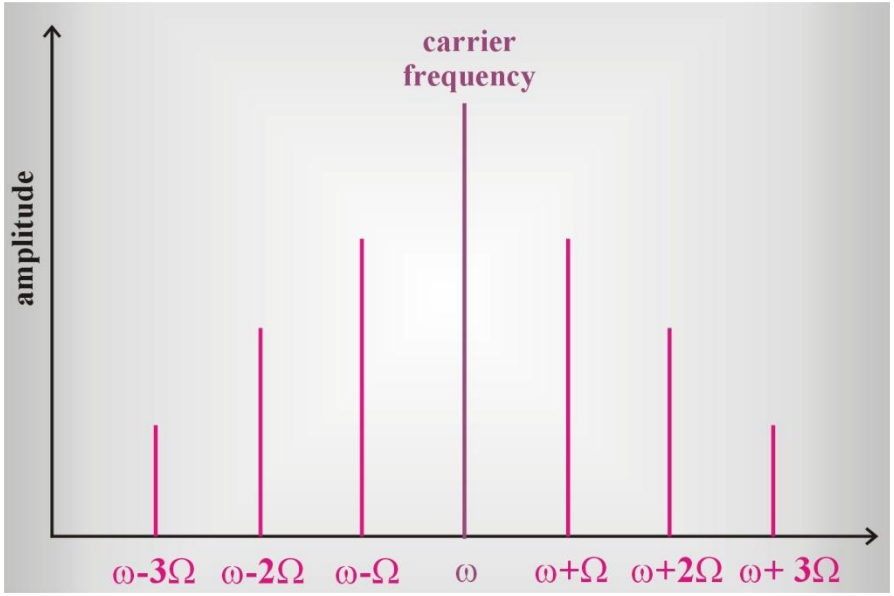
Bragg regime-
Q-switching and
cavity damping

Let us imagine that light at frequency *w* arrives to a medium characterized by a refractive coefficient . If the refractive coefficient is larger than the refractive index of the environment , the light in the medium travels n_1/n_0 times slower (since $\lambda\nu = c/n$). Let us assume that we have found a way of modulation of the refractive index n_1 with frequency Ω. The modulation causes that light in the medium propagates faster or slower according to the modulation. The modulation of the refractive index causes that the output light from the medium is also modulated. The output light is characterized by a carrier frequency ω of the incident light and a side frequency of Ω leading to appearance of additional components at the frequencies of $\omega \pm n\Omega$



Light modulation by periodical changes of the refractive index n_1

Side bands



If generated sidebands coincide with optical cavity modes - we observe the coupling between the modes and synchronization in phase.

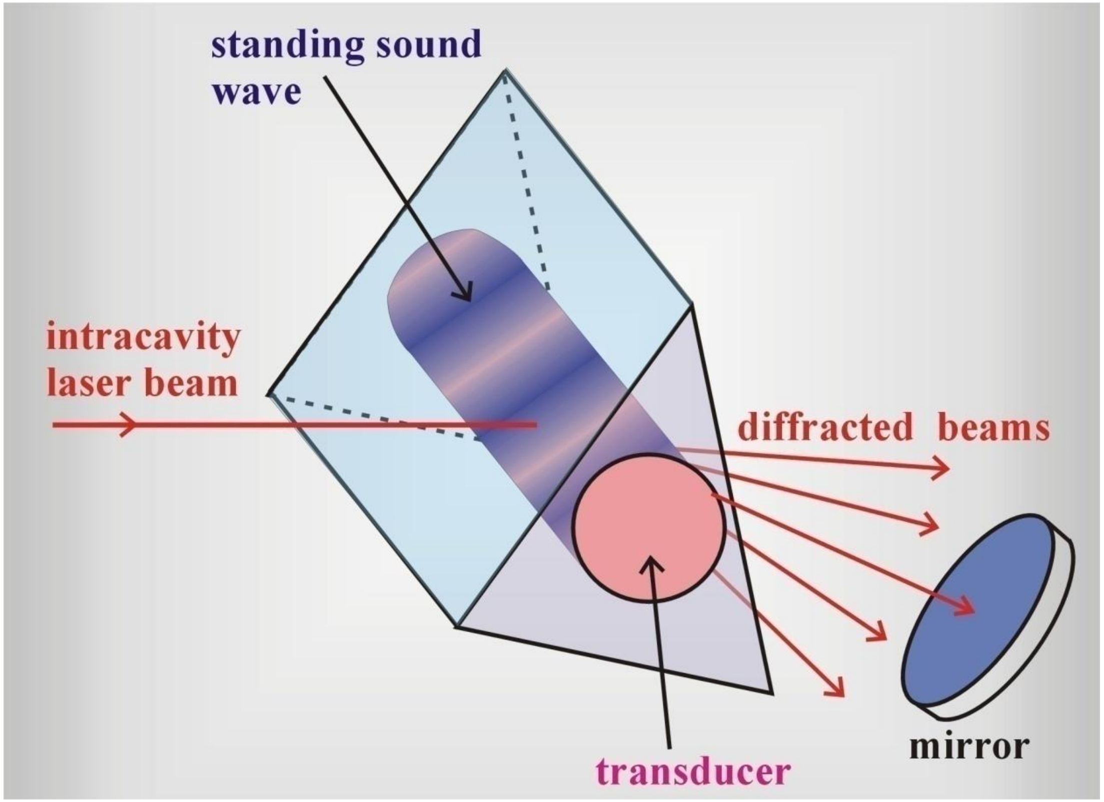
In another words- if the device modulates the gain with the intramode frequency,

$$\Delta\omega_q = \frac{c}{2L}\cdot 2\pi$$

the modelocking has been generated

G. Steinmeyer, European Virtual University, http://mitr.p.lodz.pl

Modulation of light – idea of acousto-optic devices



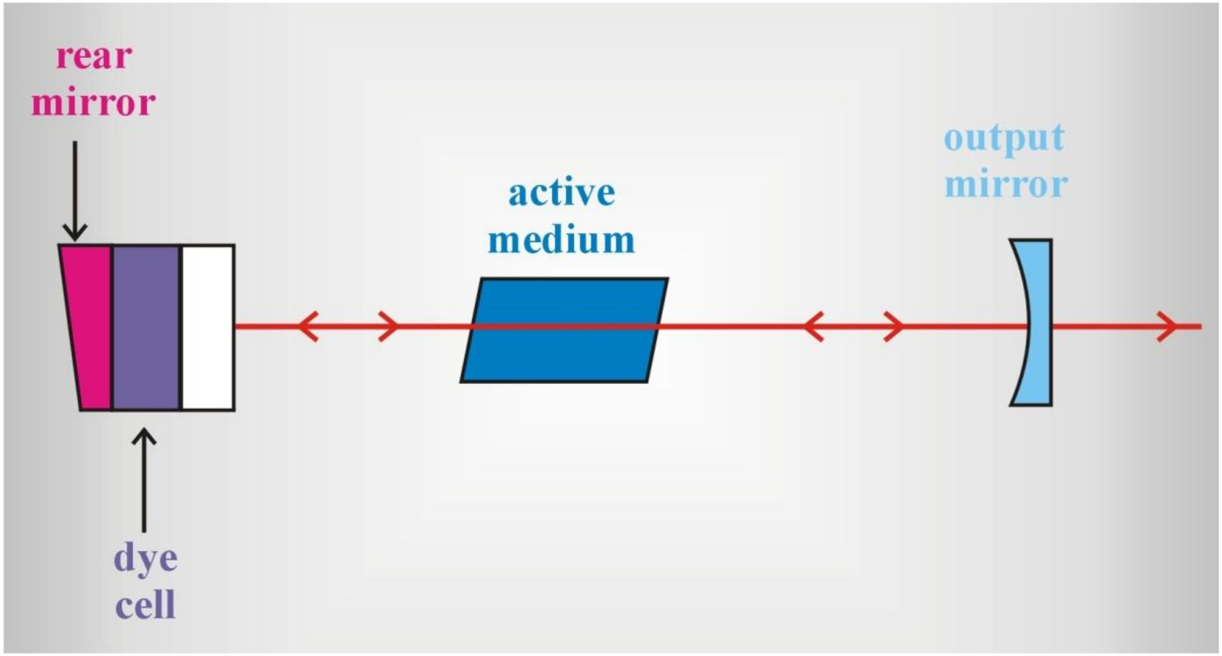
Briefly, an acousto-optic switch consists of a block of optical material (quartz, fused silica SiO_2, flint glass, tellurium dioxide) that is transparent to the laser beam. A piezoelectric transducer, usually a crystal such as lithium niobate is bonded to one side of the block *via* epoxy or vacuum metallic bonding. The radio-frequency (RF) driver generates the acoustical wave in the transducer that propagates through the medium. The radiation inside the resonator interacts with the sound wave leading to diffraction of the incident beam.

Modulation of light –electro-optic devices

POCKELS CELLS

Passive mode locking

The mechanism of the passive modelocking with the saturable dyes consists of three main steps: 1) linear amplification and linear dye absorption, 2) nonlinear absorption in the dye, 3) nonlinear amplification when the dye is entirely bleached.



Saturable absorber
SESAM- semiconductor saturable absorption mirrors

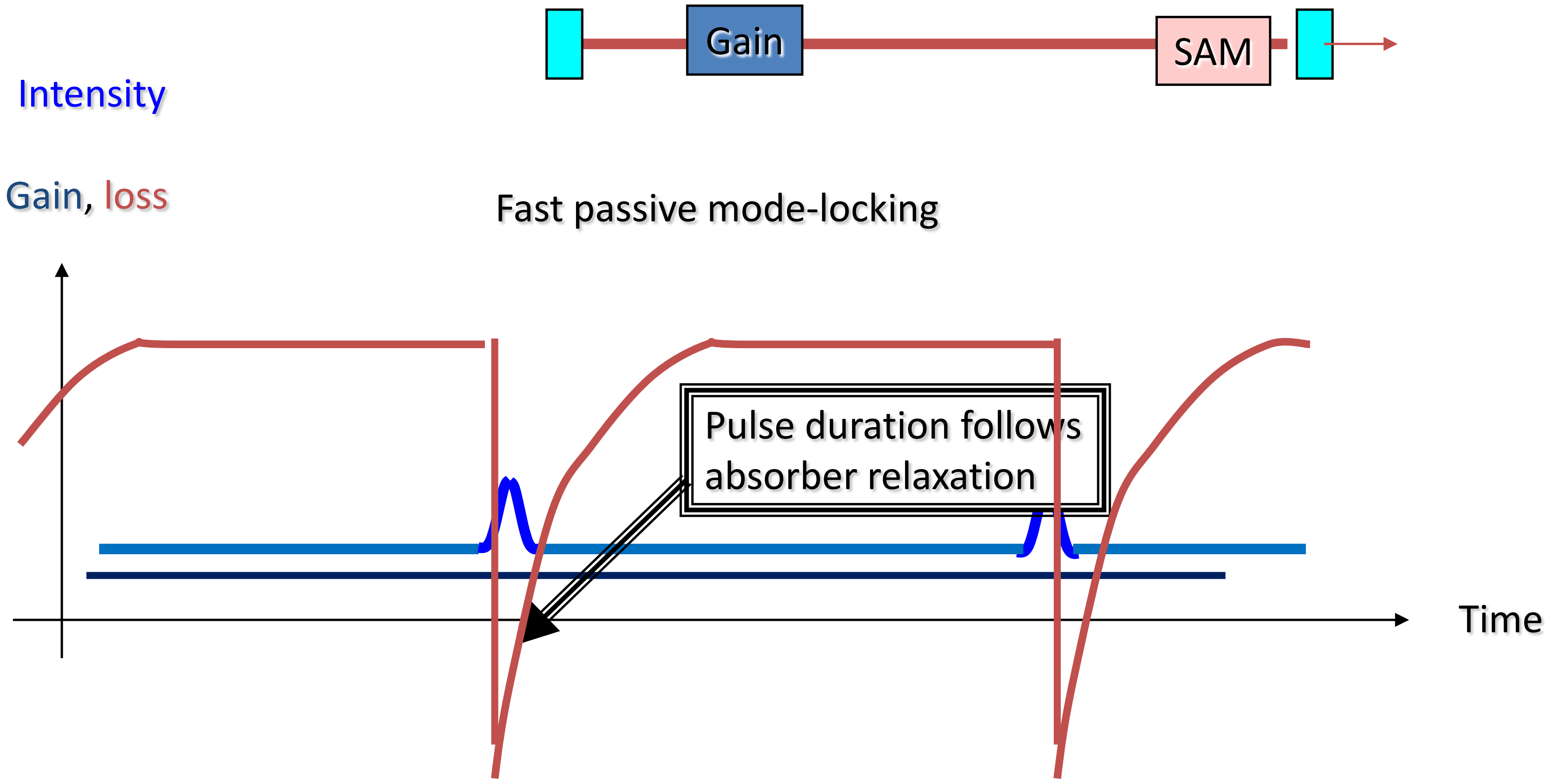
Passive mode locking

- If we want to use this method for shorter femtosecond pulses, we need a faster “shutter” than a saturable dye. In recent years this method has been replaced by continuous wave passive modelocking in solid state lasers by utilizing *nonresonant Kerr effect*
- *Kerr-lens modelocking* (KLM)

or other passive techniques like

- *saturable Bragg reflectors* (*SBR*)

Net Gain Window (fast absorber)

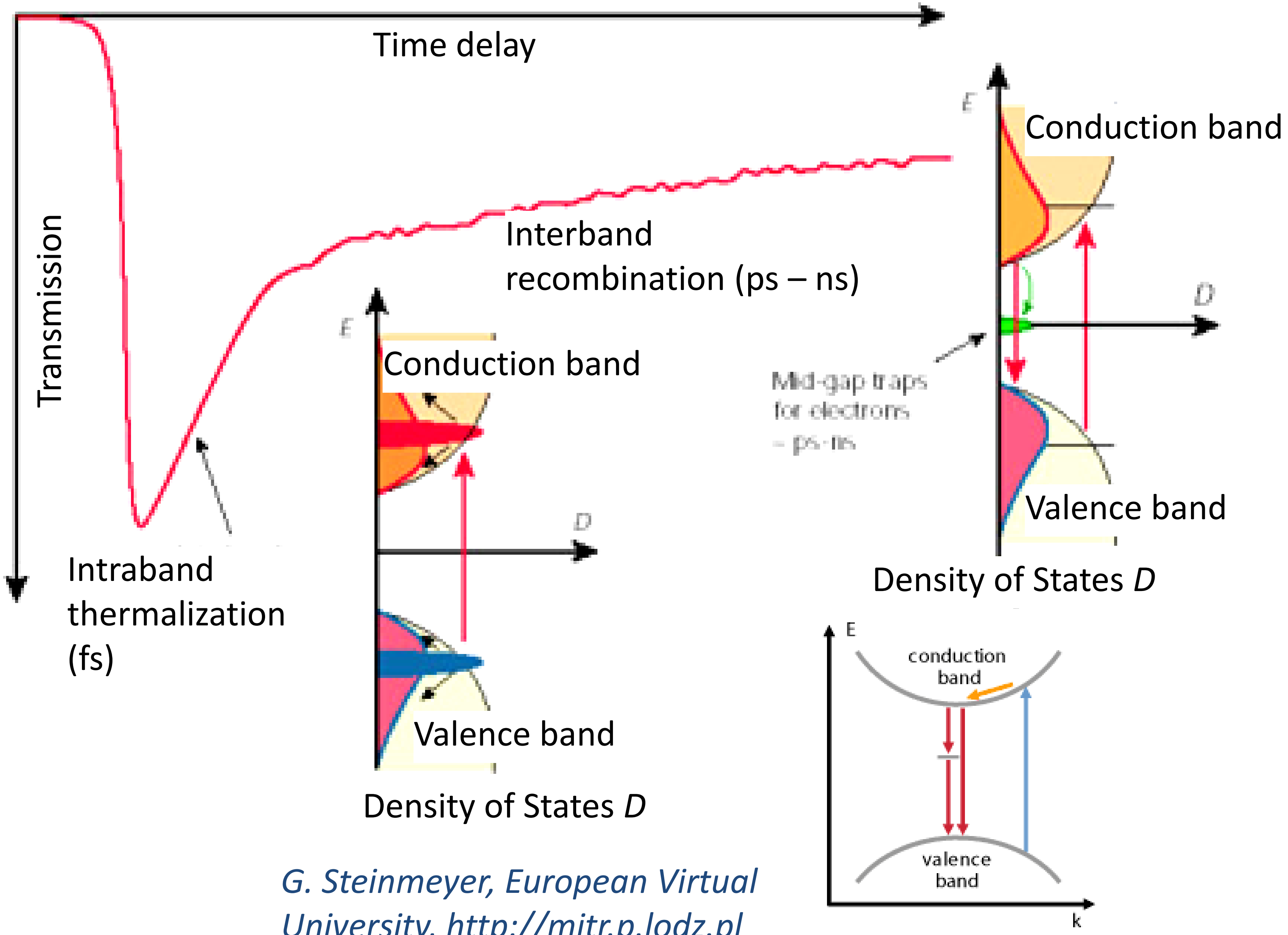

Fast passive mode-locking

Pulse duration follows absorber relaxation

H. A. Haus, *J. Appl. Phys.* 46, 3049 (1975).

G. Steinmeyer, European Virtual University, http://mitr.p.lodz.pl

Mechanism of saturable absorption (in a SESAM)



Time delay

Transmission

Interband recombination (ps – ns)

Intraband thermalization (fs)

Conduction band

Valence band

Density of States *D*

Conduction band

Valence band

Density of States *D*

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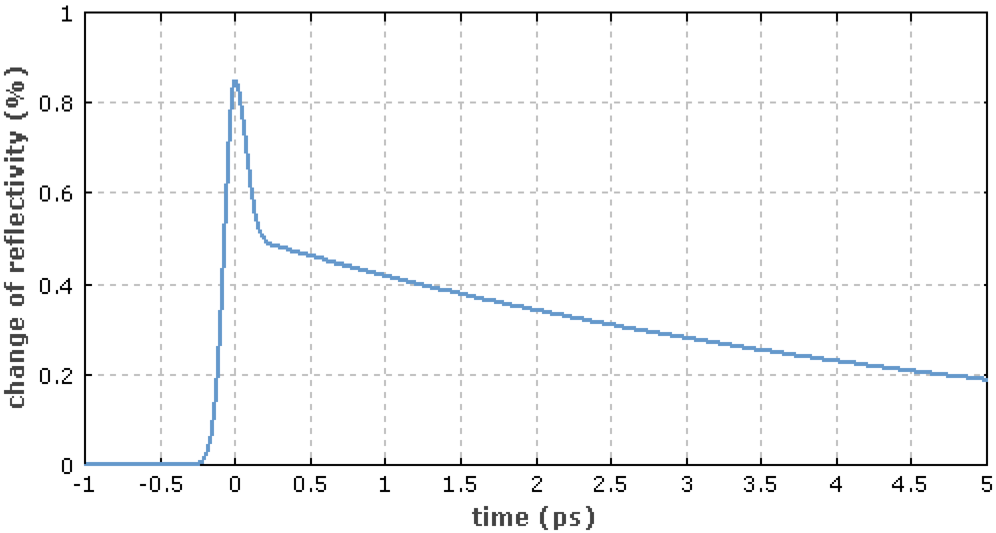
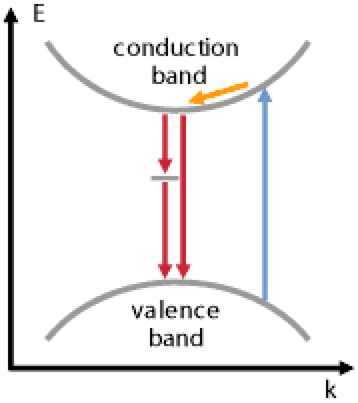
Mechanism of saturable absorption (in a SESAM)

The saturable absorption is related to an interband transition: the energy of absorbed photons is transferred to electrons, which are brought from the valence band to the conduction band. There is first some fairly rapid thermalization relaxation within the conduction and valence band within e.g. 50–100 fs, and later (often on a time scale of tens or hundreds of picoseconds) the carriers recombine, often with the aid of crystal defects.

For low optical intensities, the degree of electronic excitation is small, and the absorption remains unsaturated. At high optical intensities, however, electrons can accumulate in the conduction band, so that initial states for the absorbing transition are depleted while final states are occupied (*Pauli blocking*). Therefore, the absorption is reduced. After saturation with a short pulse, the absorption recovers, first partially due to intraband thermal relaxation, and later completely via recombination.



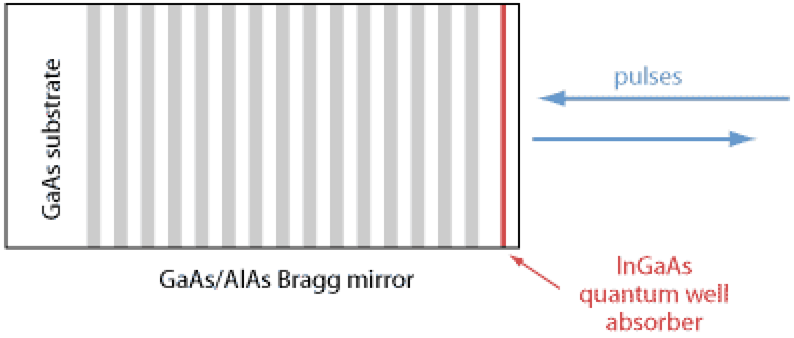


Reflectivity change of a semiconductor saturable absorber, hit by a short pulse at *t* = 0. Part of the reflectivity change disappears very quickly after the pulse, whereas another part takes many picoseconds to recover. Such curves can be recorded with pump–probe measurements.

Saturable Bragg reflector – SESAM

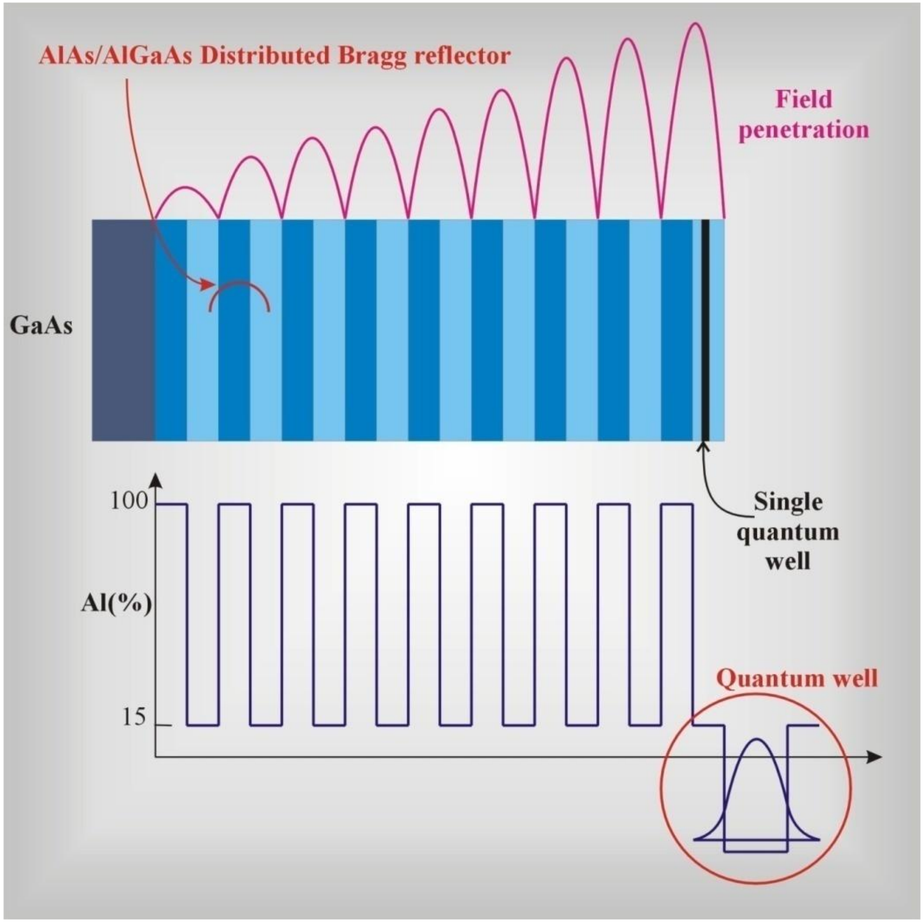
(semiconductor saturable absorber mirror)

the saturable absorber is an InGaAs quantum well (or sometimes multiple quantum wells), where the indium content is adjusted to achieve an appropriate value of the bandgap energy. The mirror structure is based on GaAs and AlAs, grown on a gallium arsenide wafer.



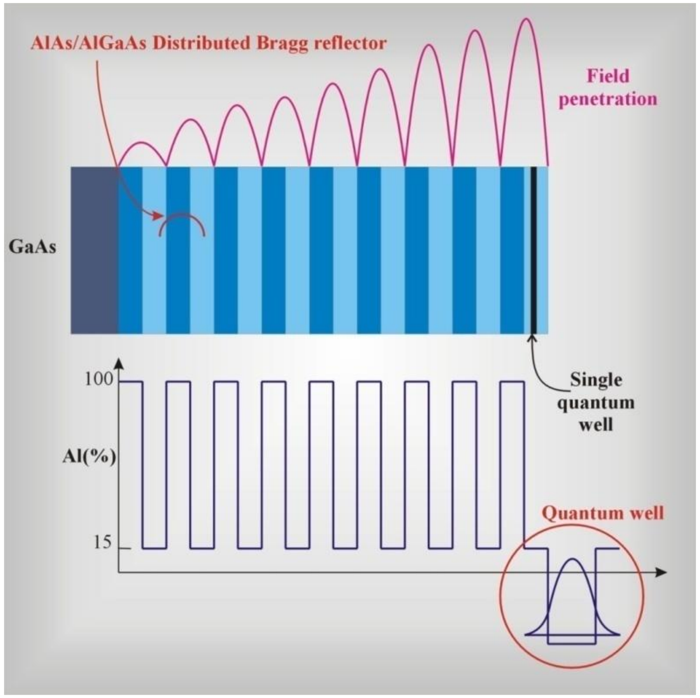
Typically, a SESAM contains a semiconductor Bragg mirror and (near the surface) a single quantum well absorber layer. The materials of the Bragg mirror have a larger bandgap energy, so that essentially no absorption occur in that region. Such SESAMs are sometimes also called *saturable Bragg reflectors* (SBRs). For obtaining a large modulation depth, as required e.g. for passive Q switching, a thicker absorber layer can be used.

Saturable Bragg reflector - SESAM



Typical saturable Bragg reflector consists of alternate layers of high- and low-index semiconductor materials, which act as a Bragg reflector and a saturable absorber layer

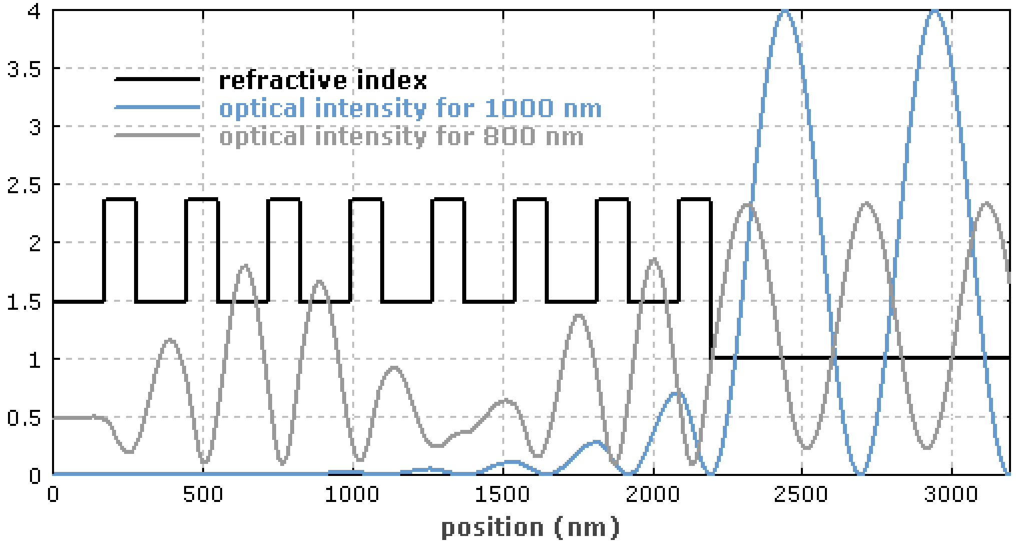
Saturable Bragg reflector - SESAM

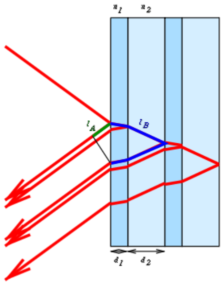


In one particular configuration, the substrate material is GaAs, with alternate layers of AlAs and AlGaAs forming a multilayer Bragg mirror (fig 3.14). Neither AlAs nor AlGaAs absorbs at 800nm. A thin AlGaAs layer of a few microns is buried in the topmost layer of this stack, acting as a quantum well with a strong absorption at 800 nm. At low laser intensities, a typical SBR has a reflectance of 95%, whereas under modelocked intensities the reflectance rises to almost 99%. Because of the multipass nature of a *cw* laser, this 4% change is more than sufficient to induce strong modelocking. Because of the absorption at 800 nm the saturable Bragg reflector has been applied in recent years in commercial Ti:sapphire laser technology. The saturable Bragg reflector method provides reliable, easy-to-use modelocked lasers for both laboratory and industrial applications.

Bragg mirror

- A Bragg mirror (also called distributed Bragg reflector) is a structure which consists of an alternating sequence of layers of two different optical materials. The most frequently used design is that of a quarter-wave mirror, where each optical layer thickness corresponding to one quarter of the wavelength for which the mirror is designed. The latter condition holds for normal incidence; if the mirror is designed for larger angles of incidence, accordingly thicker layers are needed.
- The principle of operation can be understood as follows. Each interface between the two materials contributes a Fresnel reflection. For the design wavelength, the optical path length difference between reflections from subsequent interfaces is half the wavelength; in addition, the reflection coefficients for the interfaces have alternating signs. Therefore, all reflected components from the interfaces interfere constructively, which results in a strong reflection. The reflectivity achieved is determined by the number of layer pairs and by the refractive index contrast between the layer materials. The reflection bandwidth is determined mainly by the index contrast.
- Figure 1 shows the field penetration into a Bragg mirror made of eight layer pairs of TiO_2 and SiO_2. The blue curve shows the intensity distribution of a wave with the design wavelength of 1000 nm, incident from the right-hand side. Note that the intensity is oscillating outside the mirror due to the interference of the counterpropagating waves. The gray curve shows the intensity distribution for 800 nm, where a significant part of the light can get through the mirror coating.





Bragg mirrors

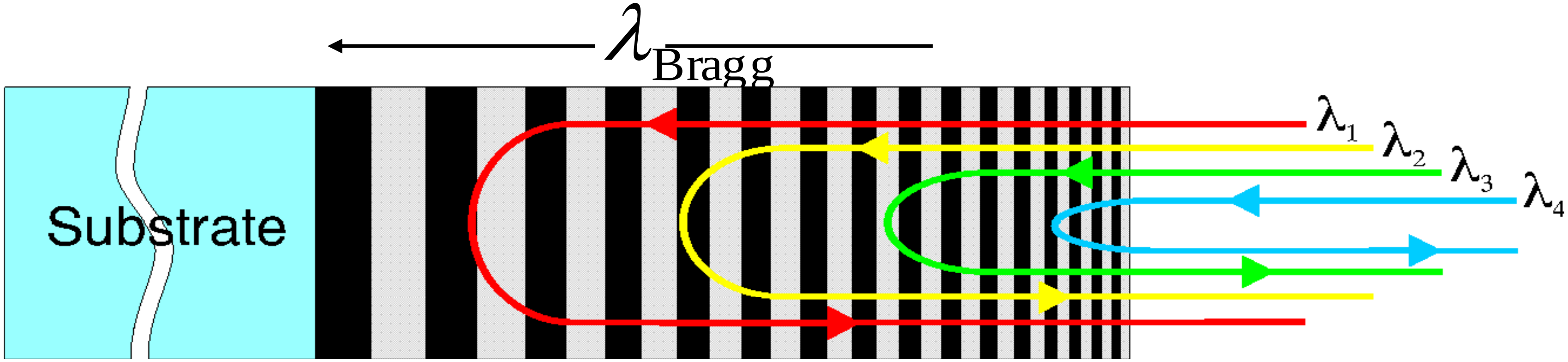
- **Types of Bragg Mirrors**
- Bragg mirrors can be fabricated with different technologies:
- Dielectric mirrors based on thin-film coating technology, fabricated for example with electron beam evaporation or with ion beam sputtering, are used as laser mirrors in solid-state bulk lasers.

- Fiber Bragg gratings, including long-period fiber gratings, are often used in fiber lasers and other fiber devices. They can be fabricated by irradiating a fiber with spatially patterned ultraviolet light. Similarly, volume Bragg gratings can be made in photosensitive bulk glass.

- There are various types of Bragg reflectors used in other waveguides, based on, e.g., corrugated waveguide structures which can be fabricated via lithography. Such kind of gratings are used in some distributed Bragg reflector or distributed feedback laser diodes.

- There are other multilayer mirror designs which deviate from the simple quarter-wave design. They generally have a lower reflectivity for the same number of layers, but can be optimized e.g. as dichroic mirrors or as chirped mirrors for dispersion compensation.

Chirped mirrors



A chirped mirror is a dielectric mirror with chirped spaces—spaces of varying depth designed to reflect varying wavelengths of lights—between the dielectric layers (stack). Chirped mirrors are used in applications like lasers to reflect a wider range of light wavelengths than ordinary dielectric mirrors, or to compensate for the dispersion of wavelengths that can be created by some optical elements

R. Szipöcs et al., *Opt. Lett.* 19, 201 (1994)

G. Steinmeyer, European Virtual University, http://mitr.p.lodz.pl

Saturable Bragg reflector - SESAM

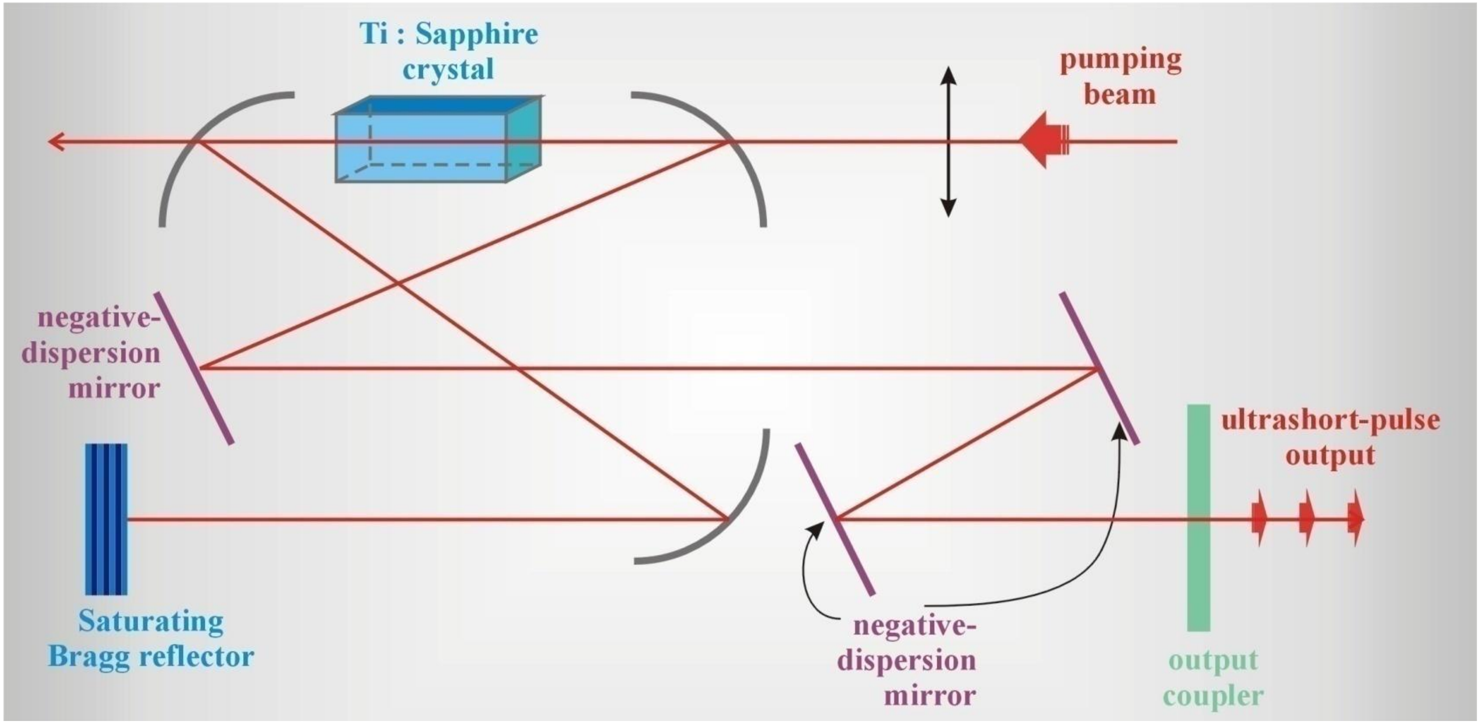
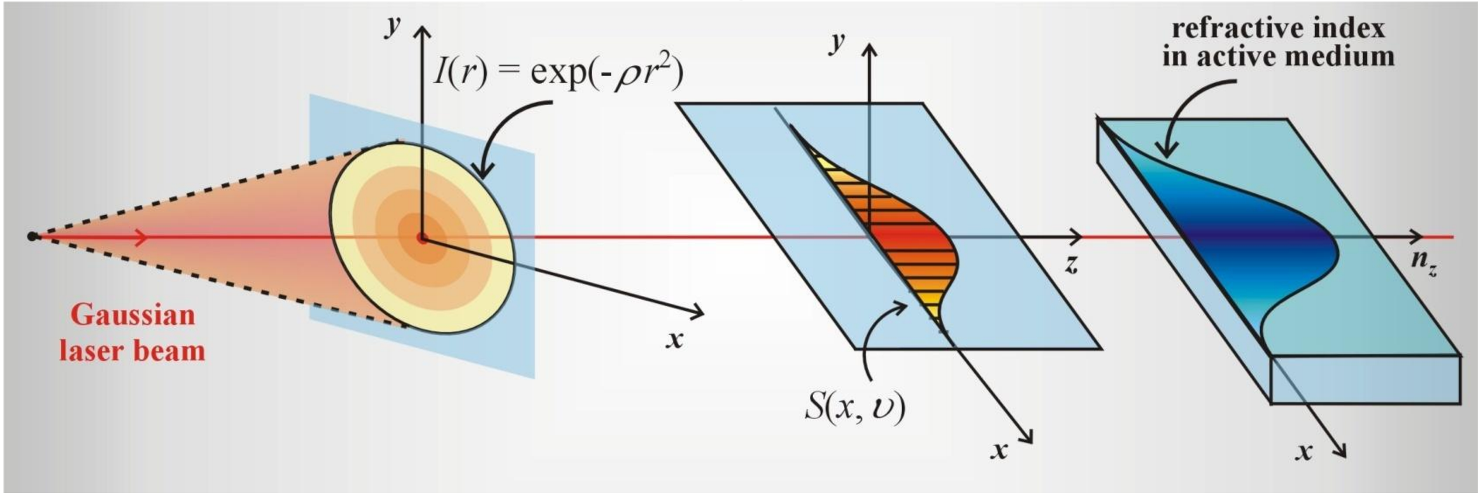


Fig. shows one of many commercial designs in which the Ti:sapphire oscillator and a solid-state pump laser are packaged in a single, compact sealed box.

Kerr self focusing lens (KLM)



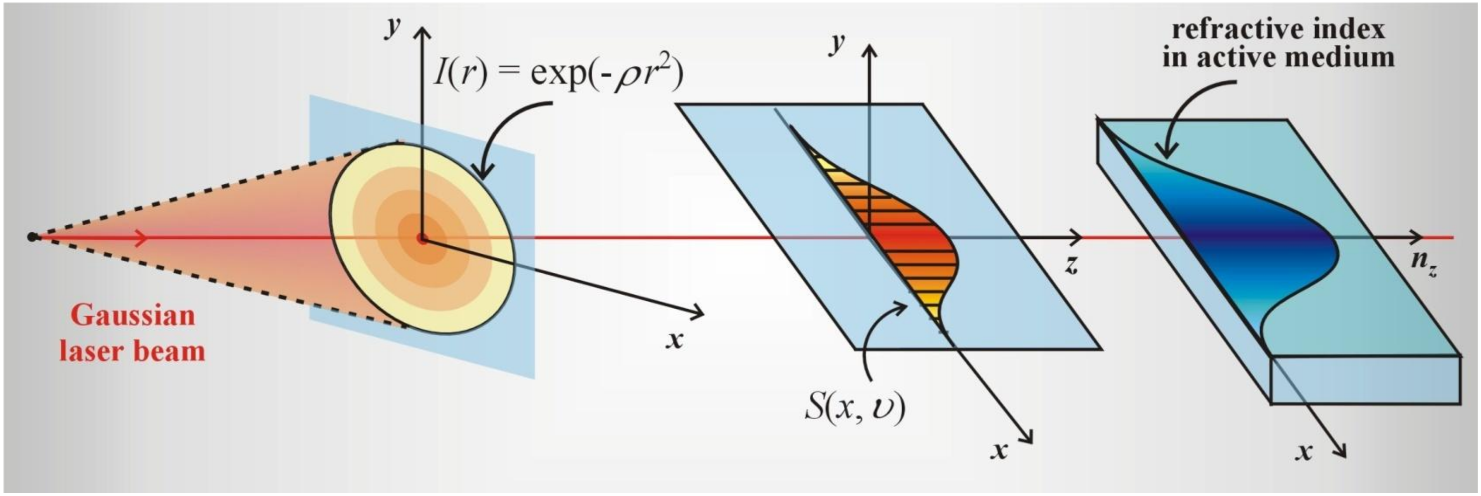
The Kerr effect, which has been known for a long time in nonlinear optics, implies that a refractive index is a function of a light intensity *I*

$$n = n_0 + n_2 I$$

It indicates that the Kerr effect leads to the intensity dependent variation of the laser beam profile. Indeed, for a Gaussian beam profile in the transverse direction the spatial index distribution can be written as

$$n(r) = n_0 + n_2 I(r)$$

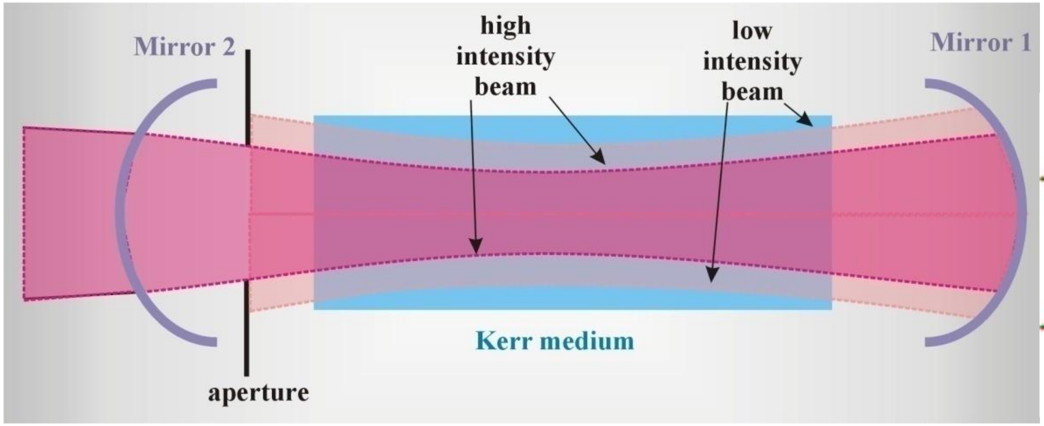
where *I*(*r*) is given by Gaussian distribution $I(r) = \exp\left(-\rho r^2\right)$

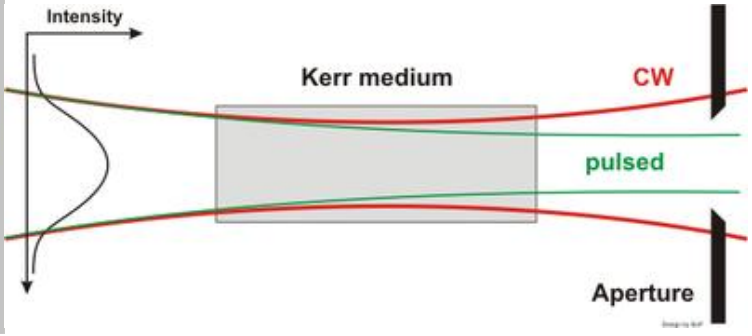


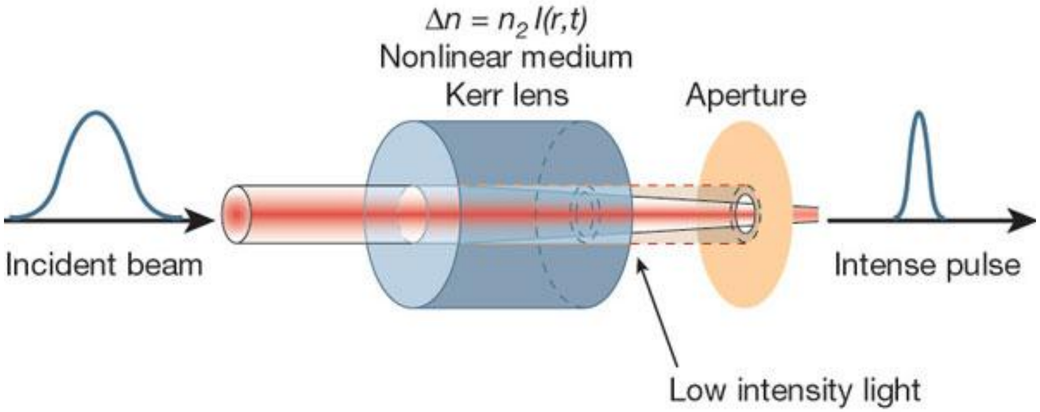
- The refractive index distribution along *x* axis for the Gaussian beam propagating along the *z* axis.

- One can see that the index modification in an active medium follows the intensity of the laser beam. For the positive term $n = n_0 + n_2 I$, the index has maximum at *x*=0 for the center of the Gaussian beam and is much smaller at the wings. Therefore, the refraction index is not homogeneously distributed in the Kerr medium and corresponds to a situation as we would insert an additional material in a shape of Gaussian lens into an optical resonator.

Kerr self focusing lens (KLM)







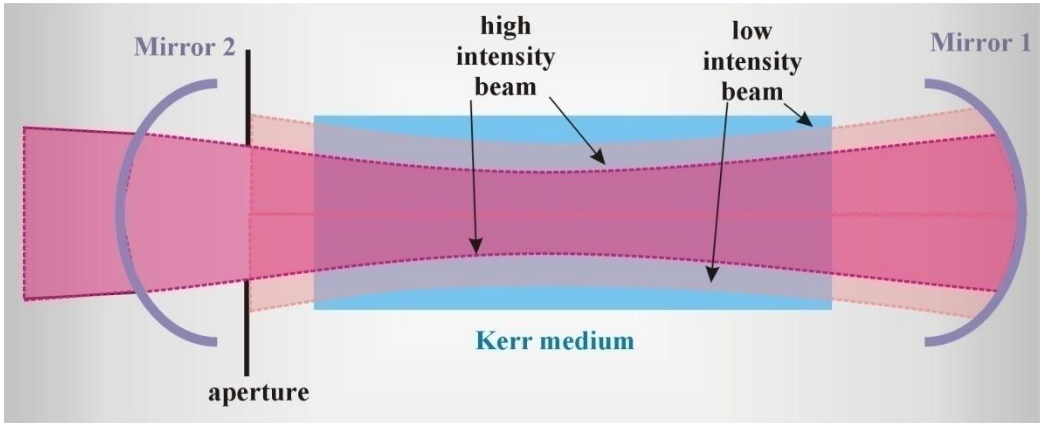
Combination of a hard aperture and the Kerr effect leads to amplitude modulation of the resonator modes with the frequency corresponding to the double round-trip time which is required to achieve modelocking

The refractive index lens formed in the Kerr medium focuses the laser beam towards a center as illustrated . If we introduce an aperture into a resonator it begins to act as a selective “shutter”.

G. Steinmeyer, European Virtual University, http://mitr.p.lodz.pl

a focal length *f* is governed by the following expression

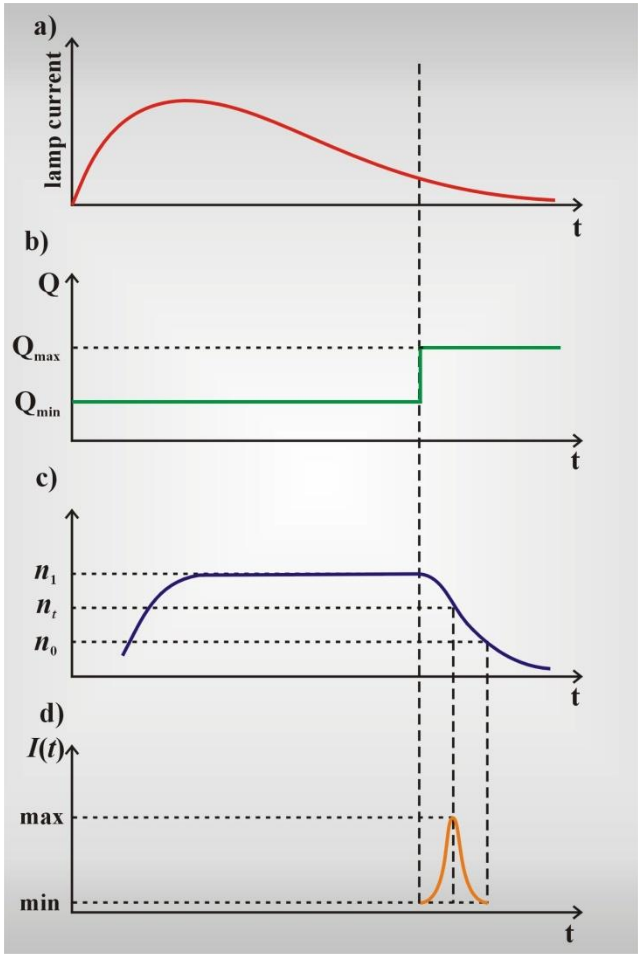
$$f = \frac{w^2}{4n_2 I_0 L}$$



where w is the beam waist, n_2 is the nonlinear index, I_0 is the peak intensity, L is the length of the active medium

- It preferentially induces more loss for the edge of the beam, which is still a continuous wave, allowing the pulsed central mode to monopolize the laser gain. The modes of higher intensity are transmitted through the aperture because of a smaller size due to the stronger Kerr lens focusing, whereas the modes of lower intensity cannot pass to the mirror M2 through the aperture and they are lost. The high intensity beam is reflected from the mirror M2 with some losses at the aperture and passes again the active medium where is amplified. The loss-amplification process is repeated every round-trip time leading to the amplitude modulation of the modes in the resonator and to the modelocking.

Q-switching

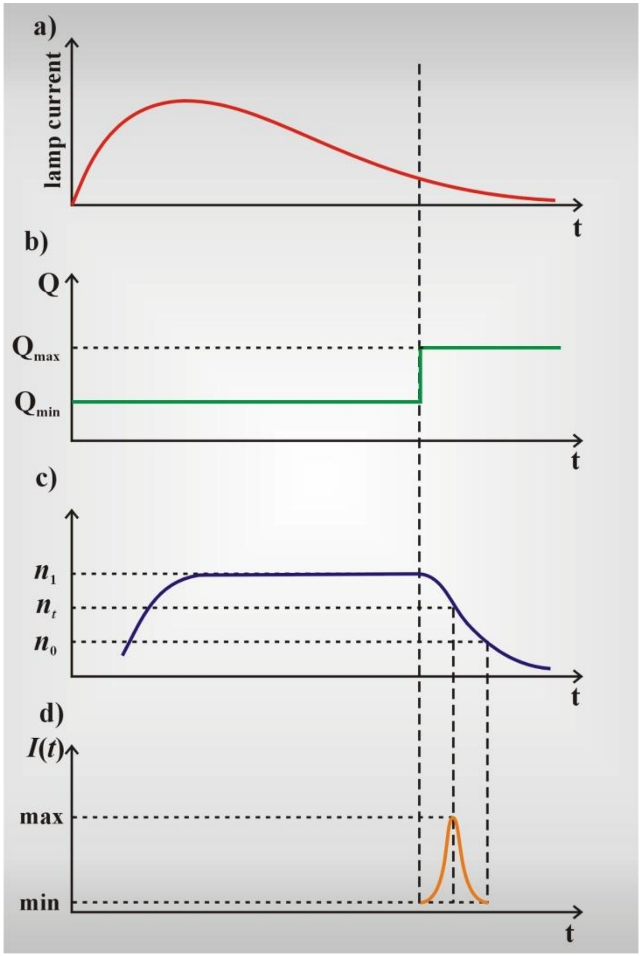


Mechanism of generation of a *Q*-switched pulse
: a) pumping, b) *Q*-switching,
c) energy storage in a three-level system, d) pulse generation

In *Q*-switching, the energy is stored in the optical cavity with the population inversion building up until the *Q*-switch is activated. Once *Q*-switch is activated, the stored energy is released in a single pulse. The higher the quality factor, the lower the losses, the more energy can be stored inside the cavity. In the *Q*-switched lasers the energy obtained from the population inversion by pumping (usually flash lamps) is stored in the active medium. Although the stored energy is far above the threshold for lasing action, the action does not start. The action is prevented by introducing to the resonator controlled losses (low *Q*). So, the gain in the resonator is high but the cavity losses are also high and the laser does not lase. The energy may be stored in the upper level as long as the pumping pulse from the flash lamp builds up and the relaxation processes do not drop back the molecules to the ground state destroying the population inversion. Roughly, this time is on the order of the lifetime of the upper state. Once the *Q*-switch is activated and the high quality factor *Q* is restored, the lasing suddenly starts and the stored energy is released in a single short, pulse. The peak power of such a pulse is extraordinary high.

$$G^{2n} = \frac{I_0^{2n}}{I_0} = (R_1 \times R_2)^n \exp\left[-2n\left(\overset{<0}{\beta} + \overset{>0}{\alpha_s}\right)l\right]$$

Q-switching



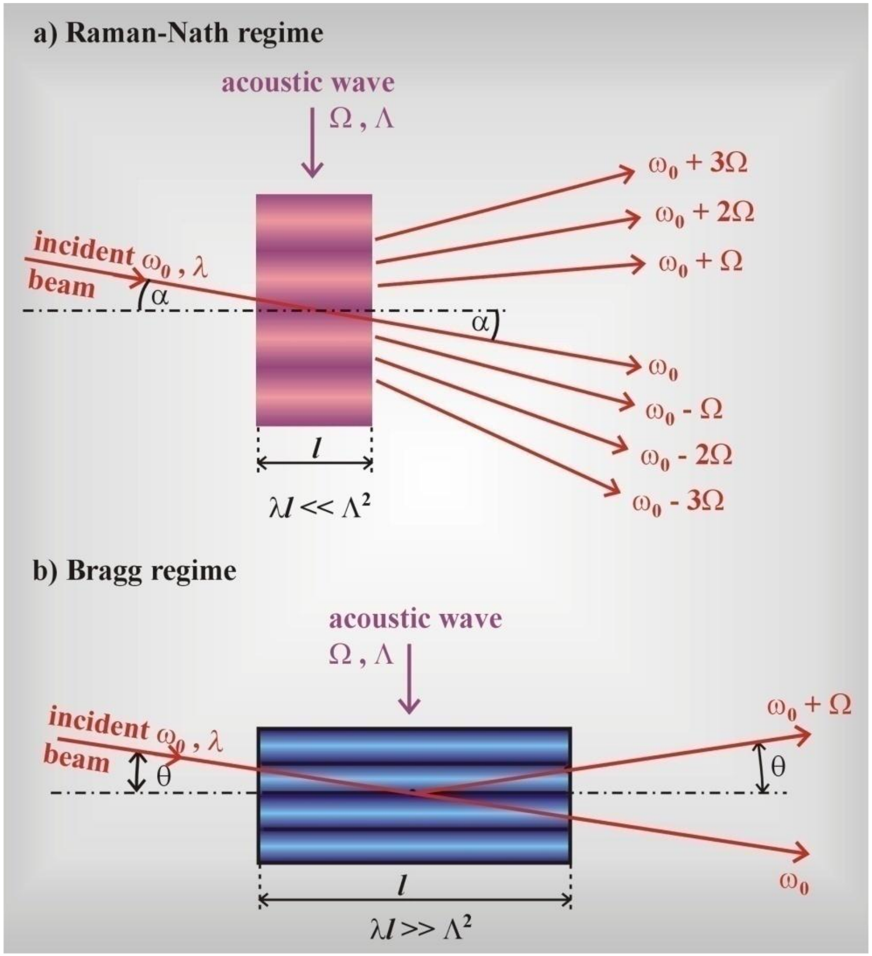
Now, when we understand the major steps in the mechanism of generation of *Q*-switched pulses we need to ask how to control the resonator quality factor *Q* and how to switch rapidly between the low and high values of *Q*.

There are several methods, including acousto-optic, electro-optic, mechanical, and dye switches. The idea of the acousto-optic modulator was explained before.

We presented the acousto-optic modulator employed in the active modelocking. We showed that the active modelocker usually works in the Raman-Nath regime in contrast to the Bragg regime that is employed in the cavity dumper and in the *Q*-switching modulators.

Mechanism of generation of a *Q*-switched pulse: a) pumping, b) *Q*-switching, c) energy storage in a three-level system, d) pulse generation

Q-switching



In contrast to the Raman-Nath regime presented before, the frequency of the acoustic wave is higher, the interaction path is lengthened and higher-order diffraction is eliminated. Only zero and first order rays are not suppressed. The diffracted beam reduces the quality of the resonator *Q*, allowing the energy to build up and store inside the resonator without lasing. When the sound wave stops to travel (transducer is switched off) the radiation beam is no longer diffracted (high *Q*) the laser begins to lase and the energy is released from the resonator in a single pulse.

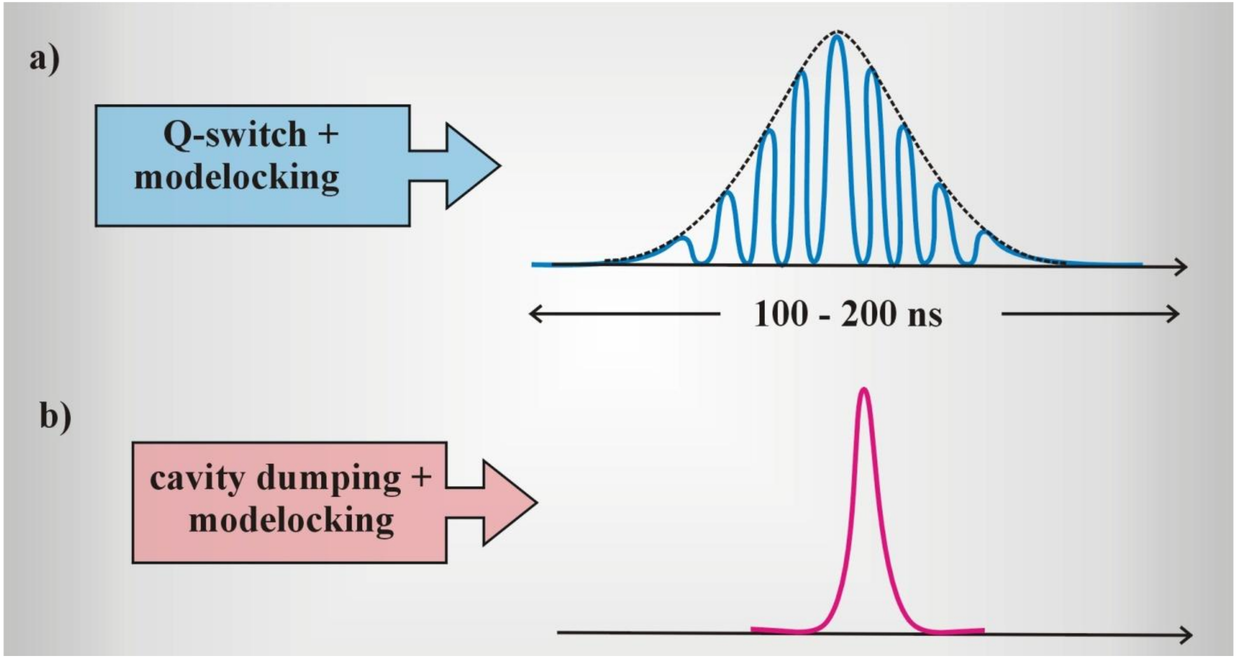
Limit cases of acousto-optic device: a) Raman-Nath regime; b) Bragg regime

Q-switching

- There are several criteria that must be taken into account to choose a proper *Q*-switch:
- upper-state lifetime; only lifetimes long enough to prevent spontaneous energy emission can be *Q*-switched,
- a gain parameter; if the gain is high, the diffracted light may not be able to prevent a feedback in the cavity leading to laser lasing,
- storage capacity; which denotes how much power the *Q*-switch will have to accommodate.
- The *Q*-switching is employed in flash lamp-pumped solid-state lasers and diode-pumped solid-state lasers such as Nd:YAG, Nd:YVO_4, Nd:YLF, as well as ruby and Nd:glass.

Cavity damping

Cavity dumping is not a technique for generation of ultrashort pulses. It is usually used to increase the pulse energy or change the repetition rate.

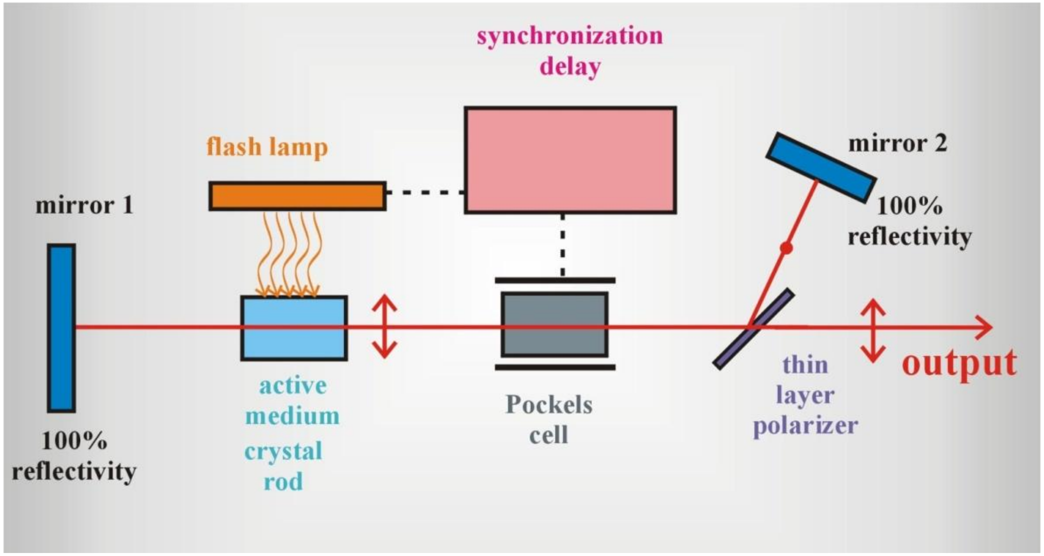


a) *Q*-switching produces a burst of modelocked pulses within the envelope of 100-200 ns *Q*-switch pulse,
b) b) cavity dumped laser produces a single modelocked pulse

I know from my own experience as a tutor that students usually do not understand the difference between the *Q*-switching and the cavity dumping. In both cases energy is stored in the resonator cavity, very often with help of the acousto-optic devices working in the same regime-Bragg refraction. What makes the distinctions and specificity of those methods? In the *Q*-switching regime the energy is “stored” in the population inversion – in the amplifying medium. During energy storing, shortly before the energy is released from the cavity, the laser does not lase, the cavity is kept below threshold conditions. Although the gain I n the active medium is high, the cavity losses (low *Q*) are also high preventing lasing action.
Contrary, in the cavity dumping mode the cavity is not kept below threshold conditions, and the laser lases all the time (both when it emits pulses or not), because the energy is stored in the optical radiation energy inside the cavity, not only in the population inversion. The only threshold that must be kept is the damage threshold for the optical elements inside the cavity.
Cavity dumping can be employed in any dye or a solid-state laser. The cavity dumping can be employed in *cw*-pumped lasers, flash lamp pumped lasers and in lasers pumped with modelocked lasers.

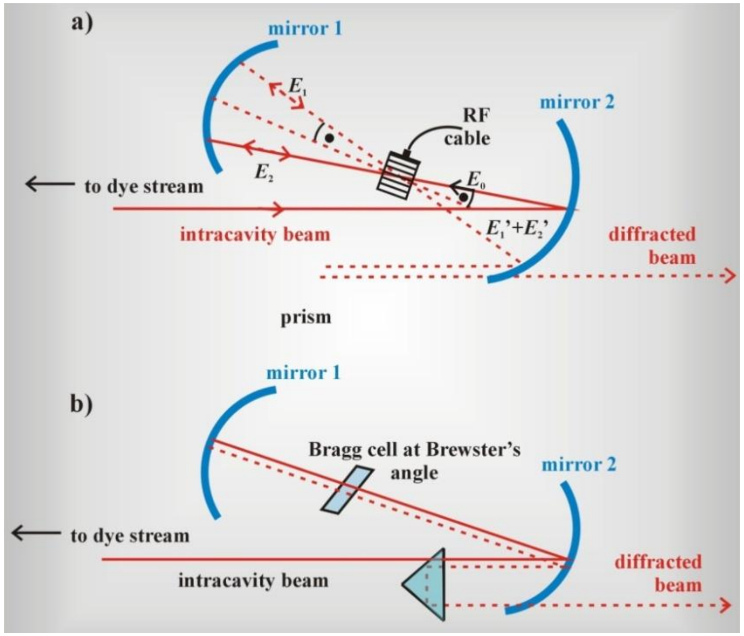
Cavity damping

The flash lamp is fired ($t = 0$), its intensity begins to increase producing fluorescence in the active medium. The horizontally polarized fluorescence (in the plane of the drawing in fig. 3.21) passes through the thin layer polarizer as a lost output light. Upon reaching the maximum lamp current ($t_1 \sim 0.8$ ms) and peak-energy storage (and maximum of population inversion) in the crystal, the Pockels cell ($l/2$) is switched on at t_1 changing the polarization of the light to the vertical one. The resulting vertically polarized light is reflected, not transmitted, by the thin-layer polarizer and reflected by the 100% R mirror M2. Therefore, the beam is kept inside the cavity leading to energy storage. When the power in the cavity reaches its peak value at t_2 ($\Delta t \sim t_2 - t_1 \cong 60$ ns for ruby laser) the Pockels cell is switched off and the polarization returns to the horizontal one. The energy stored in the cavity can now be released through the thin-layer polarizer as an output pulse. It takes roughly the round-trip time that is required to completely drain out the energy from the cavity. Thus, the pulse duration of the cavity dumped pulse is nearly completely determined by the round-trip time that depends on the resonator geometry. If we assume a 1 m long cavity, we obtain the pulse duration $t_p = 2L/c \approx 6.7$ ns. Therefore, the combination of the Pockels cell, thin-layer polarizer and 100% mirror M2 leads to the energy storage inside the cavity during the time of Δt between switching on and off the Pockels cell when the energy builds up. Within this time of ~60 ns the light passes about 60 ns / $t_p \approx 10$ times through the resonator. Without cavity dumping it would be released every round-trip time.



Optical layout for cavity dumping. Arrow ↕ illustrate the polarization in the plane of the drawing, ● – polarization perpendicular to the drawing plane

Cavity damping



The configuration of a cavity dumper: a) top view, b) side view

In the vertical dimension (side view) the Bragg cell is oriented at Brewster's angle to minimize reflective losses and favor lasing of vertically polarized light. In the horizontal dimension (top view) the Bragg cell is oriented at the Bragg angle θ (~2.3° from the normal for *l* = 600 nm and acoustic frequency Ω = 779 MHz). The incident radiation (E_0) is split into one diffracted beam (E_1) and one directly transmitted beam after crossing the modulator (E_2). The two beams are sent back upon themselves since the acousto-optic cell is placed at the center of curvature of the spherical mirror M1. They cross in the modulator for a second time. Part of the reflected light is sent back in the incident direction (E_0) to the resonator cavity, and the rest of it corresponding to the directly transmitted beam ($E_1 \rightarrow E_1'$) plus the diffracted part of E_2 (E_2') is sent out of the cavity ($E_1' + E_2'$).

$$I_{out} = |E_{out}|^2 = 4E_0^2\,\eta(1-\eta)\left[1+\cos 2(\Omega t+\phi_s+\phi_1)\right]$$

$$\eta = \frac{I_{diff}}{I_{in}}$$

The term η characterizes losses by diffraction in one passage across the Bragg cell

$$\Omega t+\phi_s+\phi = k$$

It has maximum for the values of time *t* given by

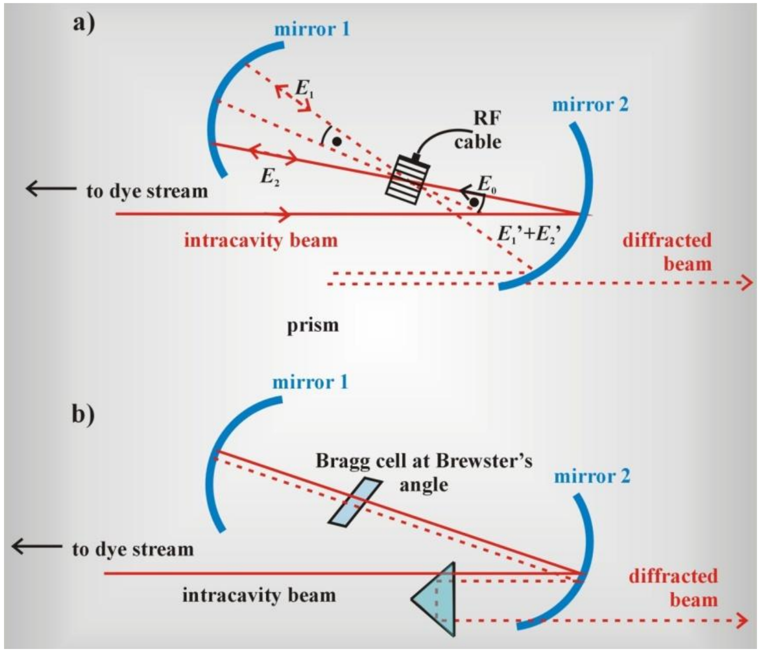
$$\Omega t+\phi_s+\phi = k+\tfrac{1}{2}$$

and minimum for *t* given by

The result obtained for the output intensity I_{out} simply says that the two diffracted beams $E_1^{'}+E_2^{'}$ can interfere with each other either constructively or destructively depending on the phase relationship between the acoustic wave ϕ_s and the light beam in the laser ϕ.

Cavity damping

- Additionally, the term $I_{out} = \left|E_{out}\right|^2 = 4E_0^2\,\eta(1-\eta)\left[1+\cos 2(\Omega t + \phi_s + \phi_1)\right]$ explains why the double passing across the Bragg cell is preferred. If we assume *h* = 0.5 for a single pass intensity diffraction, the double pass gives 100% efficiency.
- Therefore, it is possible to time the acoustic pulse in the Bragg cell relative the phase of the laser pulse such that either a maximum intensity is deflected out of the beam or essentially no intensity at all – destructive interference prevents the light from being deflected. This method is often called "*integer plus timing*". This method can be used to lower the repetition of the dye laser pumped by the high repetition modelocked lasers. It can be simply done by proper choosing the acoustic frequency with respect to the modelocked laser repetition. If the acoustic frequency has been chosen in such a way that dividing it by the modelocking frequency yields an integer *k* plus , every *k* modelocked pulse will be sent out with a maximum intensity, the other pulses will not be sent out, because their intensity will be zero.



$$\Omega t + \phi_s + \phi = k$$

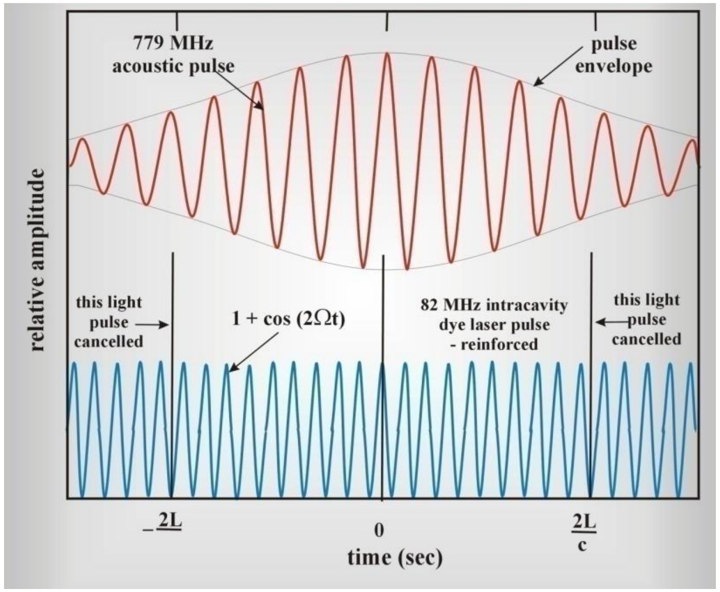
modelocked pulse will be sent out with a maximum intensity, maximum intensity is deflected out of the bam

$$\Omega t + \phi_s + \phi = k + \tfrac{1}{2}$$

No modelocked pulse will be sent out, destructive interference prevents the light from being deflected

Cavity damping-

Integer plus ½ timing



A diagram illustrating *integer plus ½ timing* in the cavity dumper. Three adjacent mode-locked dye laser pulses are illustrated in the bottom part of the figure. Since the repetition rate of the laser is 82 MHz, they are separated in time by or about 12.2 ns, where *L* is the optical cavity length of the dye laser. The acoustic pulse, which is sent down through the Bragg cell by the transducer, is illustrated in the top part of the figure. Its frequency is chosen to be 779 MHz, which when divided by the repetition rate yields 9 , an integer plus . Due to the double-pass configuration in the cavity dumper, the dye laser output consists of two light beams, one shifted up in frequency by the acoustic frequency and one shifted down. They thus interfere with one another in a manner, which modulates the output at a frequency twice that of the acoustic wave. This modulation function is shown in the bottom part of the figure. It shows how the output of the laser would be modulated, if the laser were operated with continuous light rather than modelocked. Depending on the time of arrival of the intracavity dye laser pulse relative to that of the acoustic pulse, the output pulse if either reinforced or cancelled.