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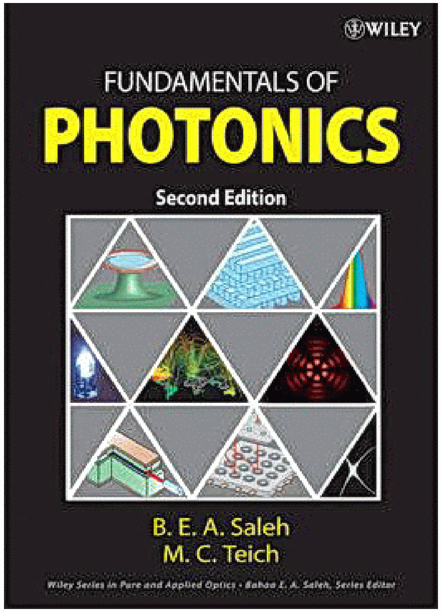
DEVELOPMENT PROGRAMME



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FUNDAMENTALS OF
PHOTONICS
Second Edition

B. E. A. Saleh
M. C. Teich

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Quantum Electronics
Lecture 6

Lasers

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HUMAN CAPITAL
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Contents

- Introduction
- Laser oscillations
- Mode-locking
- Q-switching
- Various laser systems

Saleh Ch. 13 & 14

Milestones in laser development

LASER : Light Amplification by Stimulated Emission of Radiation

1917 A. Einstein postulates stimulated emission

1954 C. H. Townes & A. L. Schawlow invented maser*

1958 A. L. Schawlow & Ch. H. Townes - laser theory

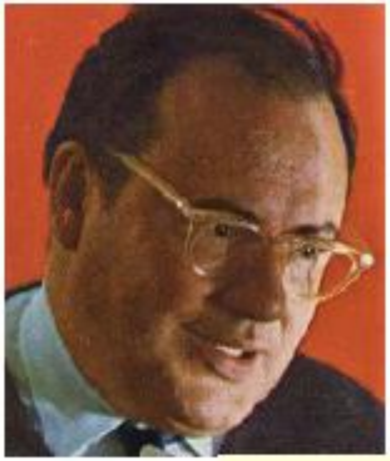
1959 G. Gould – made the first (?) laser, coined the acronym LASER

1960 T. Maiman – made the first (?) laser (in solid Ruby)

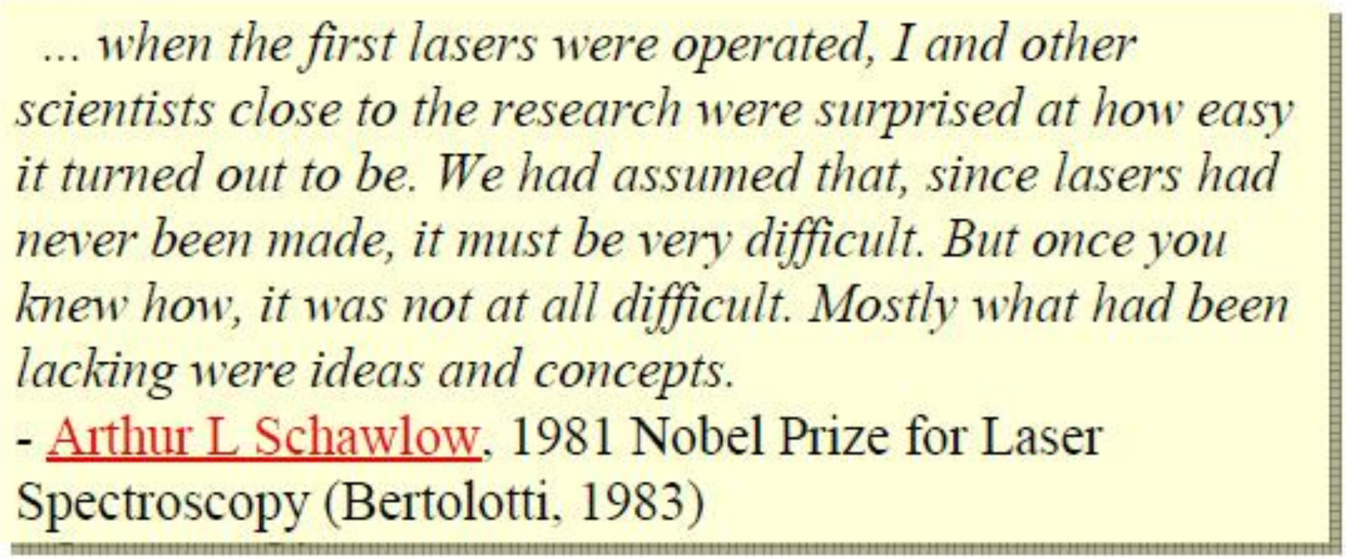
1962 R. Hall invented the semiconductor injection laser

*MASER - Microwave Amplification by Stimulated Emission of Radiation

It was not at all difficult...



Schawlow & Townes



... when the first lasers were operated, I and other scientists close to the research were surprised at how easy it turned out to be. We had assumed that, since lasers had never been made, it must be very difficult. But once you knew how, it was not at all difficult. Mostly what had been lacking were ideas and concepts.

- Arthur L Schawlow, 1981 Nobel Prize for Laser Spectroscopy (Bertolotti, 1983)

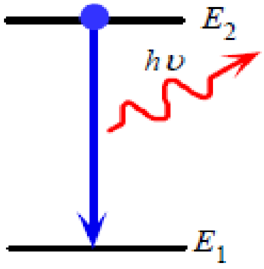
Spontaneous emision

Unavoidable when N_2 not empty

Chance of spontaneous emission per unit time is **A** (Einstein coefficient)

If there are N_2 atoms excited per volume, then Δt later we will have less, or

$$\Delta N_2 \approx -A \Delta t N_2$$



In differential form this becomes a rate equation of the form

$$\left(\frac{dN_2}{dt}\right)_{sp} = -AN_2 = -\frac{N_2}{\tau_{sp}}$$

where A is the rate constant for spontaneous emission and
τ_{sp} is the time constant for spontaneous emission given by $\tau_{sp}=1/A$

$$\boxed{N_2(t) = N_2(0)e^{-t/\tau_{sp}}}$$

Stimulated emission

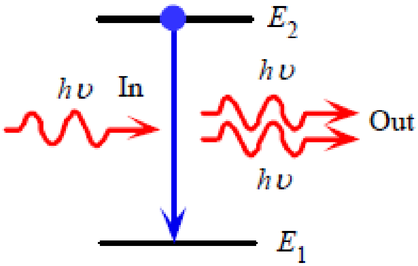
Takes place when N2>N1 and when there are photons of energy E_2-E_1 Photons generated under atom relaxation are identical (coherent) to those that stimulate the process

Scales with the spectral density of electromagnetic energy: $\rho(\nu)$

$\rho(\nu)d\nu$ - *energy per unit volume in the frequency range* $\{\nu, \nu + d\nu\}$

$$\frac{dN_2}{dt} = -N_2 W_{21}(\nu); \qquad \boxed{W_{21} = B_{21}\rho(\nu)}$$

Einstein postulate

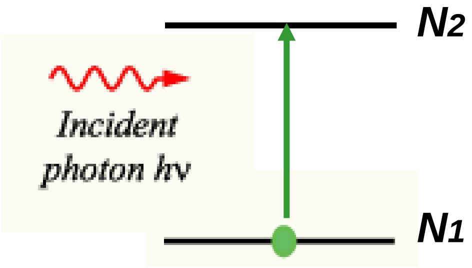


B_{21} - ***Einstein coefficient*** *for stimulated emission*

Stimulated (induced) absorption

Important for optical pumping

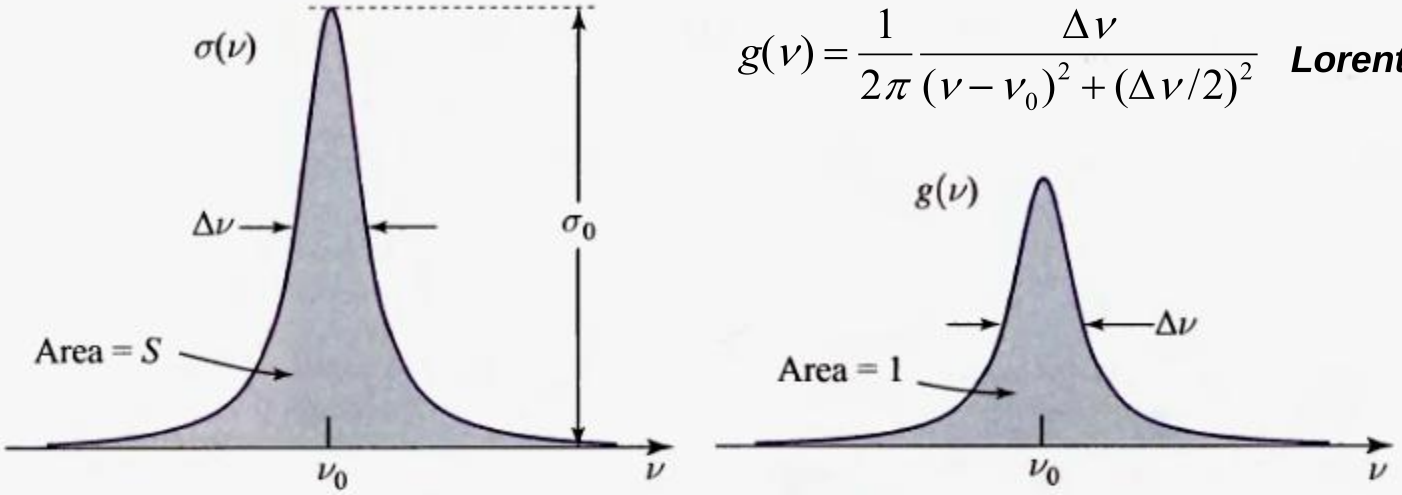
$$\frac{dN_2}{dt} = N_1 W_{12}(\nu); \qquad W_{12} = B_{12}\rho(\nu)$$



Relation between Einstein coefficients:

$$\boxed{\begin{gathered} B_{12} = B_{21} = B \\ \frac{A}{B} = \frac{8\pi h n^3 \nu^3}{c^3}; \end{gathered}}$$

Transition cross-section and lineshape function



$$g(\nu) = \frac{1}{2\pi}\frac{\Delta\nu}{(\nu-\nu_0)^2+(\Delta\nu/2)^2}$$ ***Lorentzian***

Saleh **Figure 13.3-5** The transition cross section $\sigma(\nu)$ and the lineshape function $g(\nu)$.

$$\sigma(\nu) = Sg(\nu)$$

S – transition strength

g – transition profile

Stimulated processes for monochromatic light

Stimulated emission: $\frac{dN_2}{dt} = -N_2\sigma(\nu)\frac{I(\nu)}{h\nu}$ ***adding to field***

Stimulated (induced) absorption: $\frac{dN_2}{dt} = N_1\sigma(\nu)\frac{I(\nu)}{h\nu}$ ***subtracting from field***

σ *- stimulated emission / absorption cross-section* I *- signal intensity*

ν *- light frequency* $I/h\nu$ *- photon flux*

$$\frac{dI}{dz} = (N_2 - N_1)\sigma(\nu)I \quad \Leftrightarrow \quad \frac{dI}{dz} = \gamma(\nu)I \quad with \quad \gamma = (N_2 - N_1)\sigma(\nu)$$

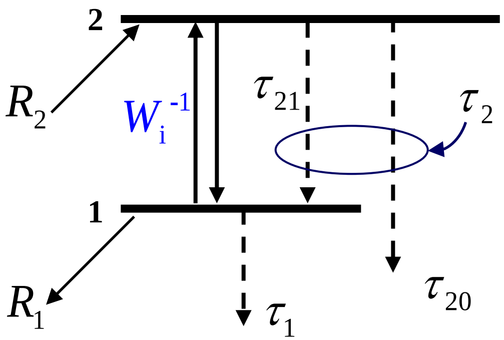
γ *-* ***gain*** *coefficient if* $(N_2 - N_1) > 0$ *or* ***loss*** *coefficient if* $(N_2 - N_1) < 0$

To find $(N_2 - N_1)$ *one needs to solve rate equations*

Rate Equations

$$\frac{dN_2}{dt} = R_2 - \frac{N_2}{\tau_2} - N_2 W_i + N_1 W_i$$

$$\frac{dN_1}{dt} = -R_1 - \frac{N_1}{\tau_1} + \frac{N_2}{\tau_{21}} + N_2 W_i - N_1 W_i$$



Steady State:

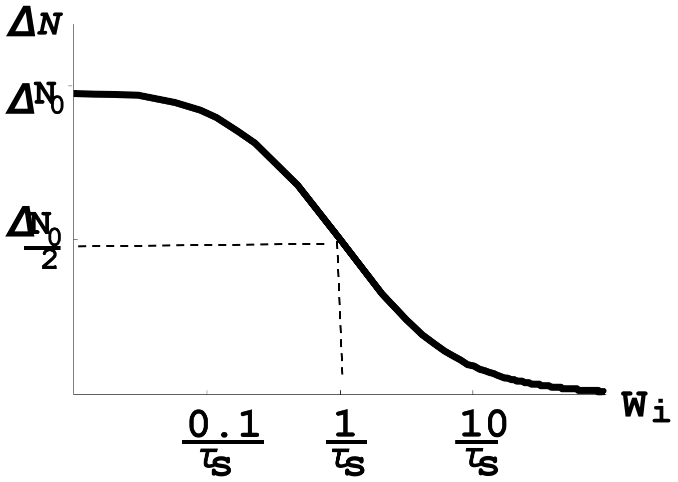
$$\frac{dN_i}{dt} = 0 \Rightarrow \boxed{\Delta N = \frac{\Delta N_0}{1+\tau_s W_i}}$$

Population inversion

$$\frac{1}{\tau_2} = \frac{1}{\tau_{21}} + \frac{1}{\tau_{20}}$$

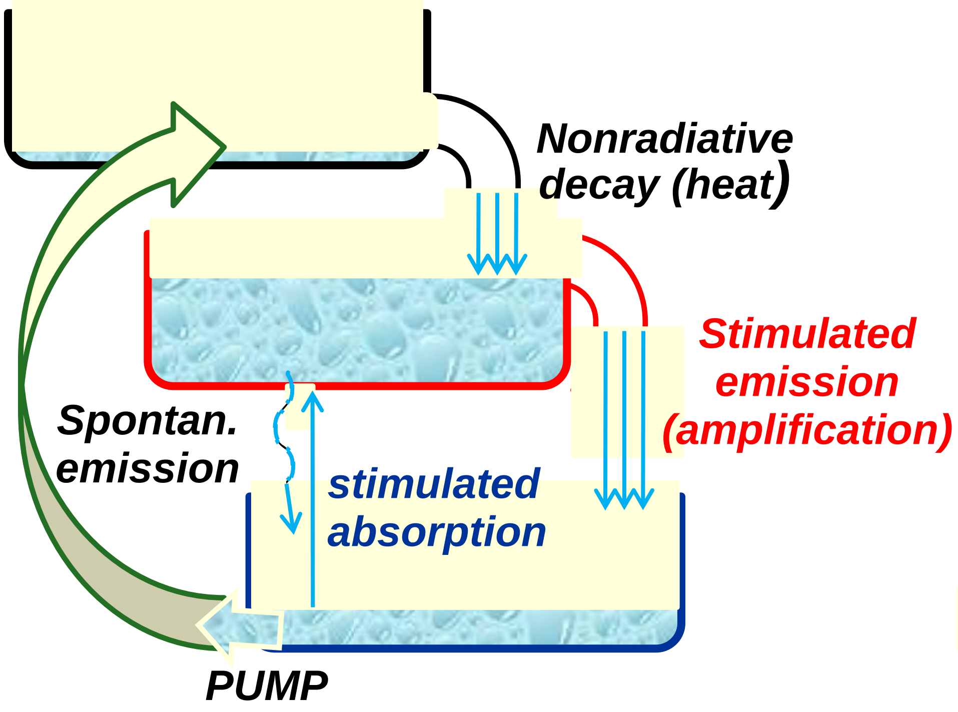
$$\text{where } \tau_s = \tau_2 + \tau_1\left(1 - \frac{\tau_2}{\tau_{21}}\right)$$

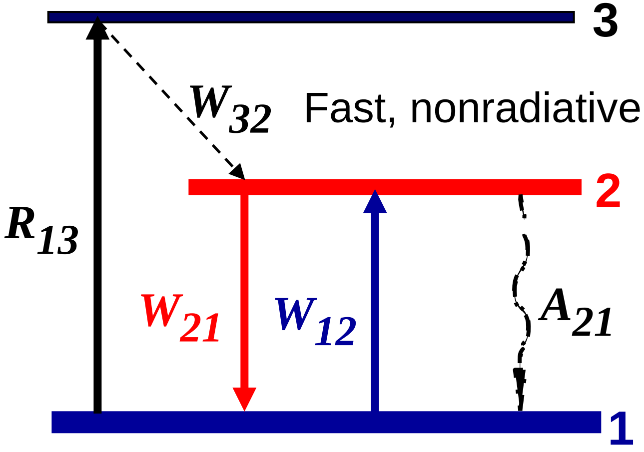
$$\text{and } \Delta N_0 = R_2\tau_2\left(1 - \frac{\tau_1}{\tau_{21}}\right) + R_1\tau_1$$



- **Steady-state Population Differences**
  - **$\Delta N_0 = N_2 - N_1$ w/o amplifier radiation**
  - **$\Delta N = N_2 - N_1$ w/ amplifier radiation**
- **τ_s – Saturation Time Constant**

Population dynamics – 3 level system





$A_{21} \propto 1/\tau_{21}$; $\tau_{21} \approx 10\,\mathrm{ms}$

$W_{32} \propto 1/\tau_{32}$; $\tau_{32} \approx 6\,\mu s$

$$\downarrow$$

$$\boxed{N_3 \approx 0}$$

$$\frac{dN_1}{dt} = -R_{13}N_1 - W_{12}N_1 + W_{21}N_2 + A_{21}N_2$$

$$\frac{dN_2}{dt} = +W_{32}N_3 + W_{12}N_1 - W_{21}N_2 - A_{21}N_2$$

$$\frac{dN_3}{dt} = R_{13}N_1 - W_{32}N_3$$

W_{ki} **- *probability of transition*** $k \rightarrow i$

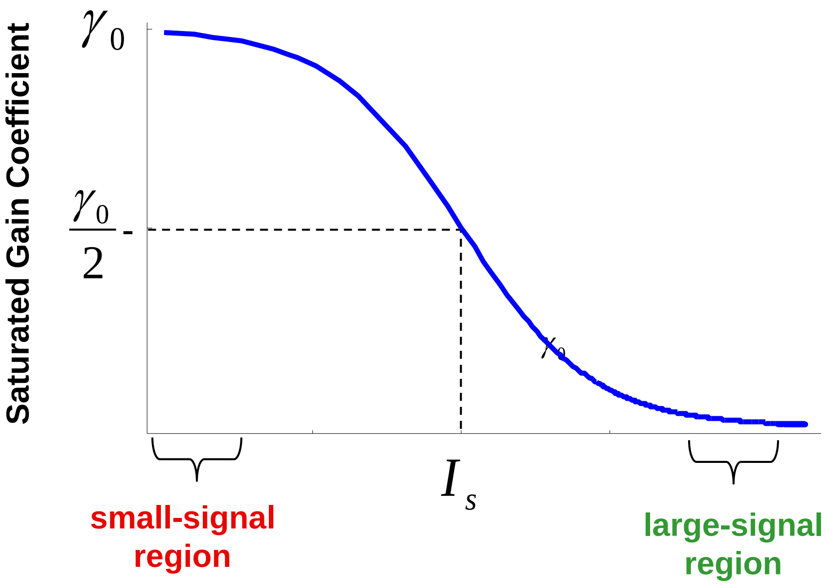
$$N_1 + N_2 + \cancel{N_3} = N_0$$ ***Total Er density conserved***

Saturated Gain Coefficient

$$\gamma(\nu) \propto N_2 - N_1$$

$$= \frac{\gamma_0(\nu)}{1 + I / I_s(\nu)}$$

γ_0 ***Gain coefficient at low intensities*** $I_0 << I_s$

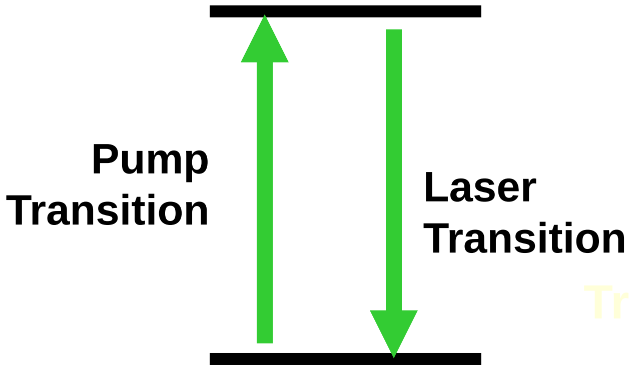


$$I(z) = I_0 e^{\gamma_0(\nu)z}$$ **small-signal**

$$I(z) = I_0 + \gamma_0(\nu) I_s z$$ **large-signal**

Inversion in two-, three-, and four-level systems

Two-level system

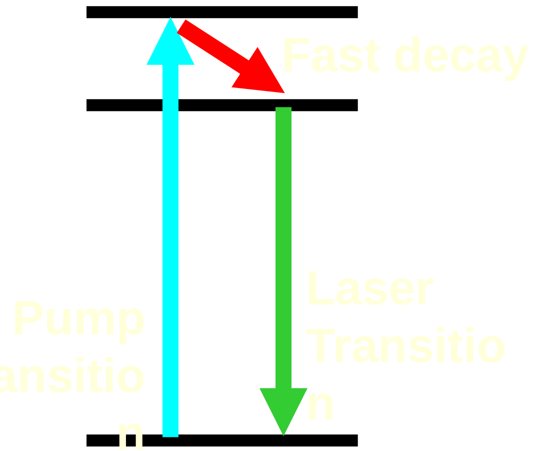


At best, you get equal populations

No lasing

$$\Delta N = -\frac{N}{I / I_s + 1}$$

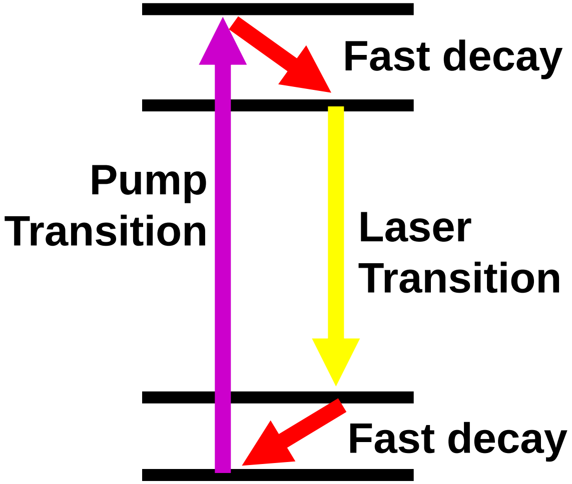
Three-level system



If you hit it hard, you get lasing

$$\Delta N = N \frac{I / I_s - 1}{I / I_s + 1}$$

Four-level system



Lasing is easy!

$$\Delta N = N \frac{I / I_s}{I / I_s + 1}$$

Laser principle

A laser is a medium that stores energy, surrounded by two mirrors.
A partially reflecting output mirror lets some light out.

I_0

I_1

I_3

I_2

R = 100%

Laser medium
with gain, G

R < 100%

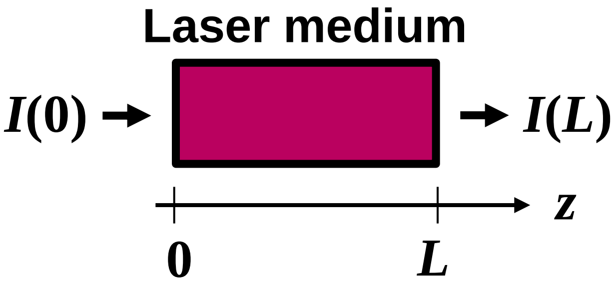
A laser will lase if the beam increases in intensity during a round trip: $I_3 \geq I_0$

Usually, additional losses in intensity occur, such as absorption, scattering, and reflections. In general, the laser will lase if, in a round trip:

Gain > Loss

This is called achieving **Threshold**

Laser gain



Neglecting spontaneous emission:

$$\frac{dI}{dt} = c\frac{dI}{dz} \propto BN_2I - BN_1I$$

[Stimulated emission minus absorption]

$$\propto B\left[N_2 - N_1\right]I$$

The solution is:

absorption/gain cross-section, σ

$$I(z) = I(0)\exp\left\{\sigma\left[N_2 - N_1\right]z\right\}$$

Gain and absorption coefficients

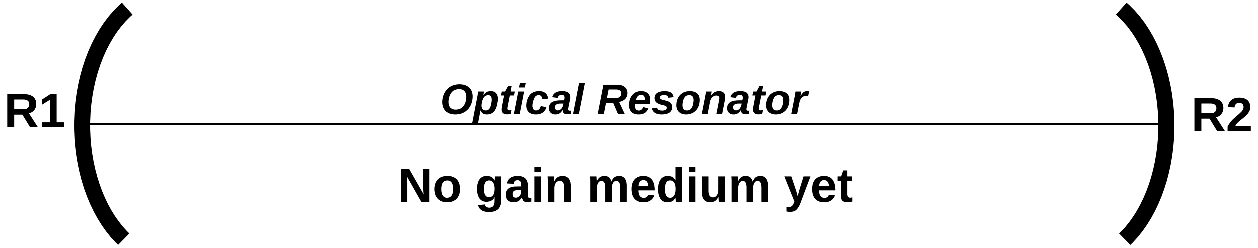
If $N_2 > N_1$: $g \equiv \left[N_2 - N_1\right]\sigma$

If $N_2 < N_1$: $\alpha \equiv \left[N_1 - N_2\right]\sigma$

Gain

$$G \equiv \exp\left\{\sigma\left[N_2 - N_1\right]L\right\}$$

"Cold" cavity



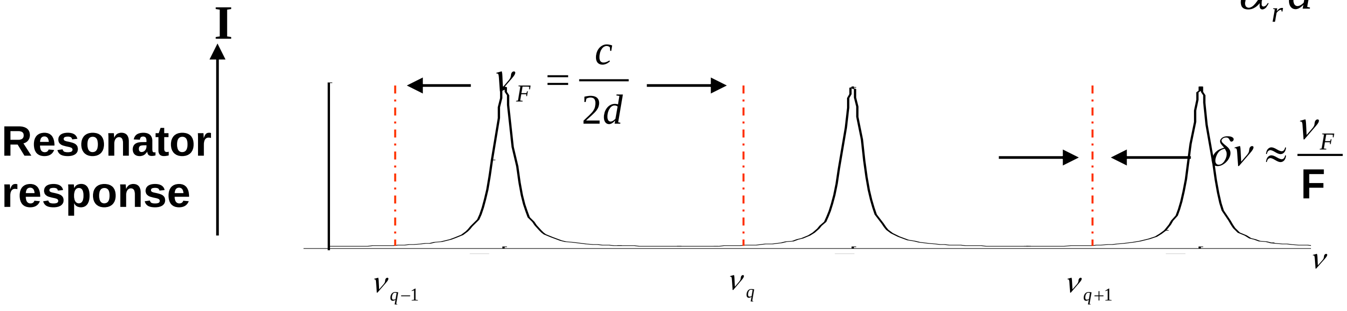
Phase-shift Coefficient $k = \frac{2\pi\nu}{c}$

Loss Coefficient $\alpha_r = \alpha_s + \frac{1}{2d} \ln \frac{1}{\mathbf{R}_1 \mathbf{R}_2}$

$$I = \frac{I_{\max}}{1 + (2\mathbf{F}/\pi)^2 \sin^2(\pi\nu/\nu_F)}$$

Photon Lifetime $\tau_p = \frac{1}{\alpha_r c}$

Finesse $\mathbf{F} \approx \frac{\pi}{\alpha_r d} = 2\pi \tau_p \nu_F$



Conditions for Laser Oscillations

- **Gain Condition: Laser Threshold**

Threshold Gain: $\gamma_0(\nu) = \alpha_r$

$$\Rightarrow N_0 = N_t \quad \text{where } N_t = \frac{\alpha_r}{\sigma(\nu)} = \frac{1}{c\tau_p\sigma(\nu)}$$

- **Phase Condition: "Hot" cavity modes**

Round-Trip Phase: $kd\left(1+\frac{X'(\nu)}{2n^2}\right) = q\pi \qquad q = 1, 2, 3\ldots$

X' -***Real part of susceptibility close to atomic line center***

This phase correction pulls lasing frequencies towards medium resonance

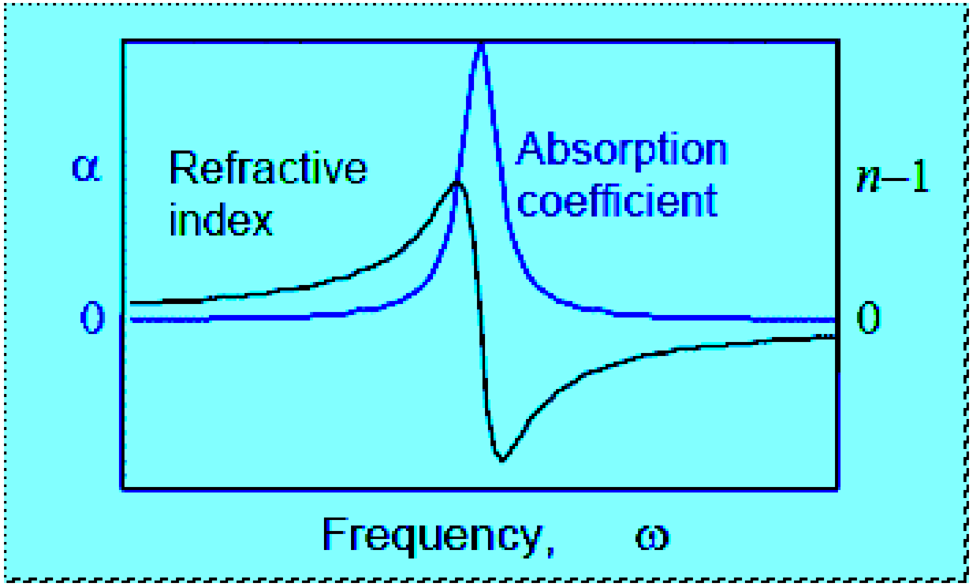
Frequency pulling

Complex refractive index

$$\left.\begin{array}{l} P = Np = N\alpha E \\ P = \varepsilon_0 \mathrm{X} E \end{array}\right\} \longrightarrow \varepsilon \equiv \varepsilon_0 n^2 = \varepsilon_0 (1 + \mathrm{X}) = \varepsilon_0 (1 + N\alpha / \varepsilon_0)$$

When X<<1:

$$n' = \mathrm{Re}\, n' - i\, \mathrm{Im}\, n' = 1 + \frac{Ne^2(\omega_0^2 - \omega^2)}{2m\varepsilon_0[(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2]} - i\frac{Ne^2\gamma\omega}{2m\varepsilon_0[(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2]}$$



Absorption coefficient:

$$\alpha(\omega) \equiv \frac{4\pi}{\lambda} \mathrm{Im}\, n$$

$$I(z) = I(0)\exp(-\alpha z)$$

Far from resonances the imaginary part becomes negligible

Frequency pulling

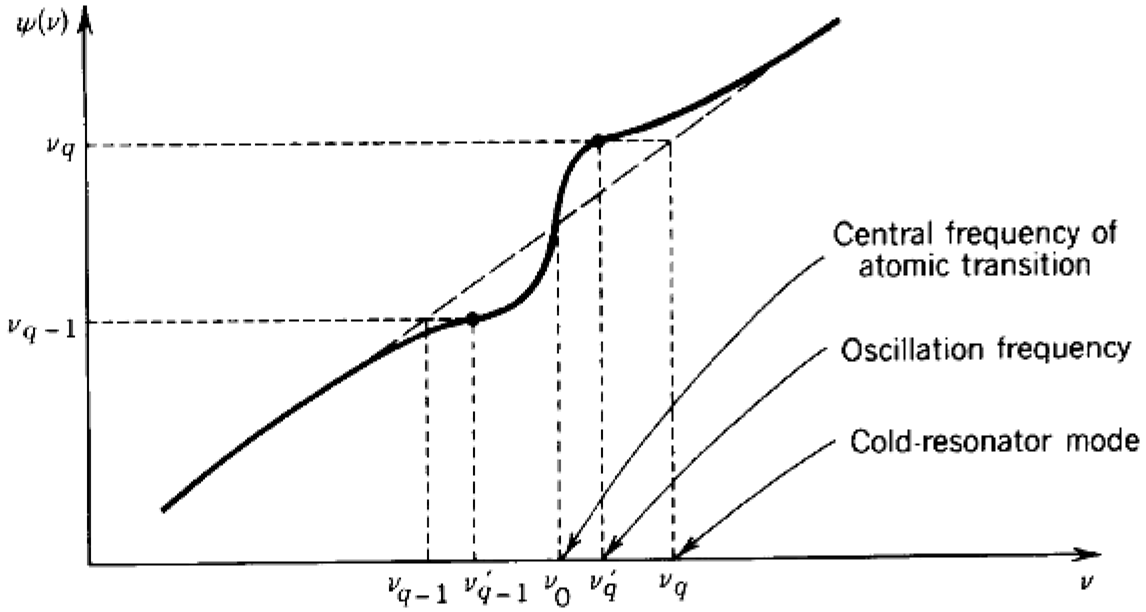
$$\underbrace{\nu + \frac{c}{2\pi n}\frac{\nu - \nu_0}{\Delta\nu}\gamma(\nu)}_{\Psi(\nu)} = \nu_q$$

'Cold' resonator mode

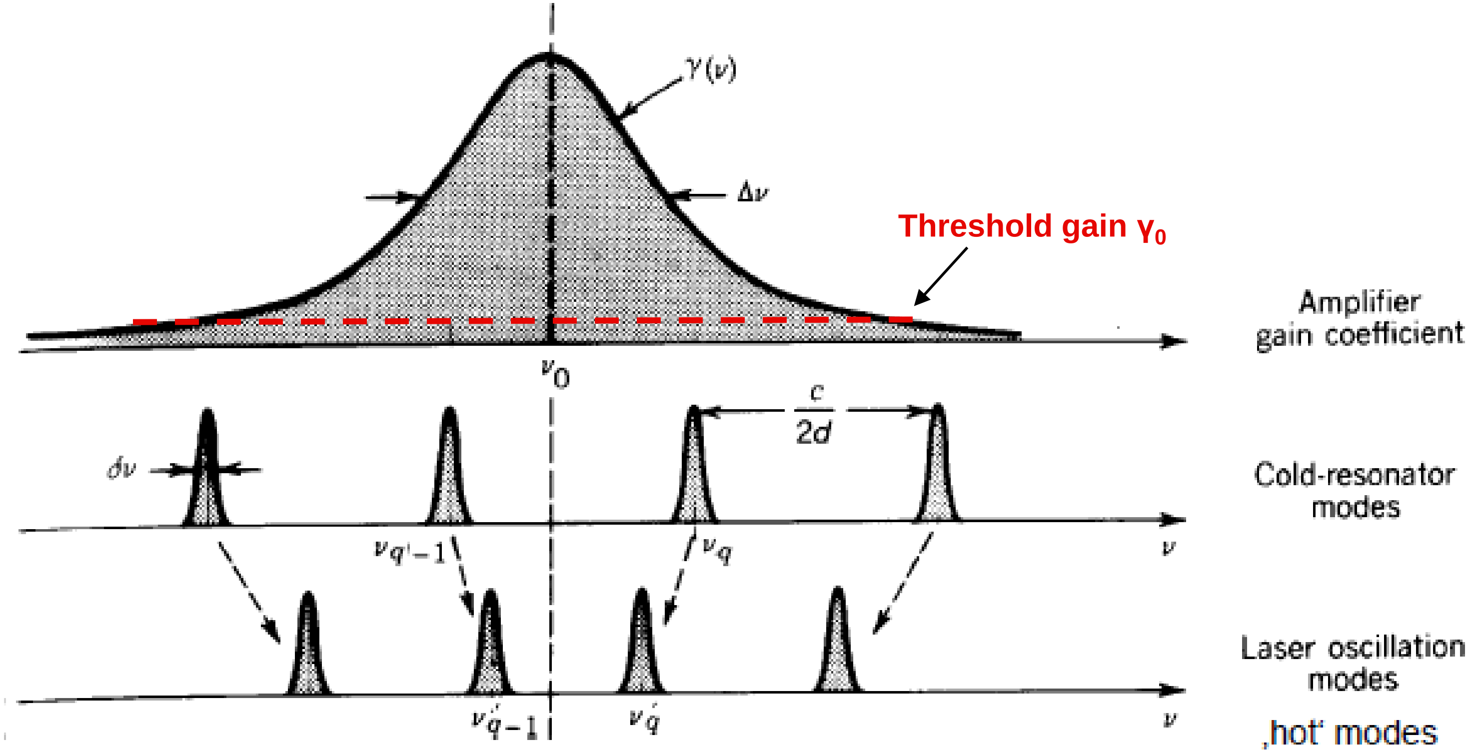
'Hot' resonator mode

$\nu_q \rightarrow \nu_q`$

$\nu_{q-1} \rightarrow \nu_{q`-1}$



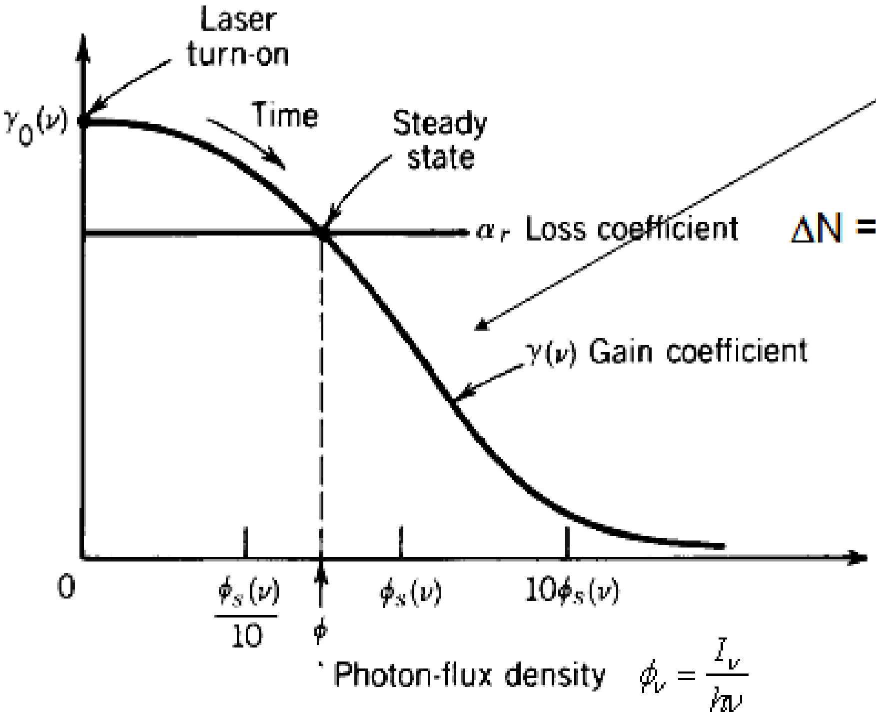
Cold- and Hot-resonator modes



For homogeneously broadend gain modes compete for the same gain and only the one that experiences strongest gain survives – single frequency lasing

Gain clamping

In a steady-state operation laser gain is clamped exactly to the value of the optical resonator losses

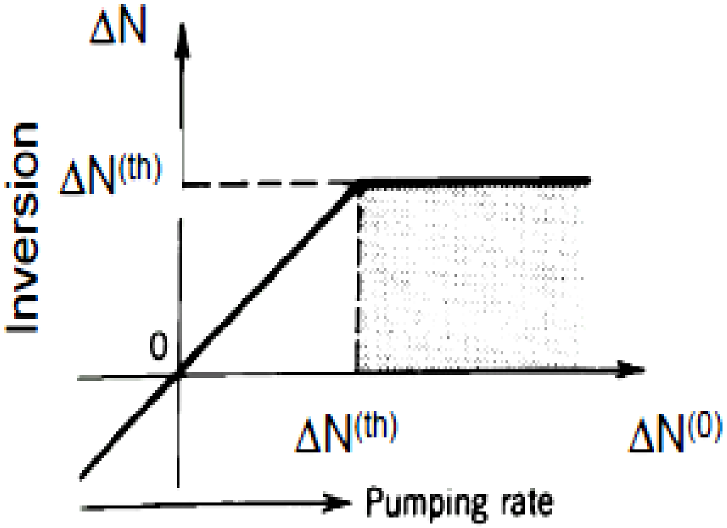


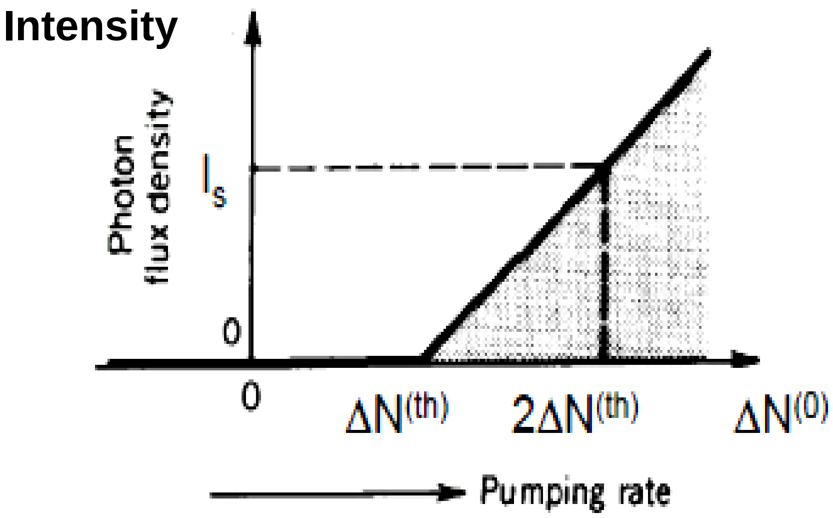
$$\gamma = \gamma_0 \frac{1}{1 + I/I_s}$$

$\Delta N = \Delta N^{th}$

$$\alpha_R = \gamma_0 \frac{1}{1 + I/I_s}$$

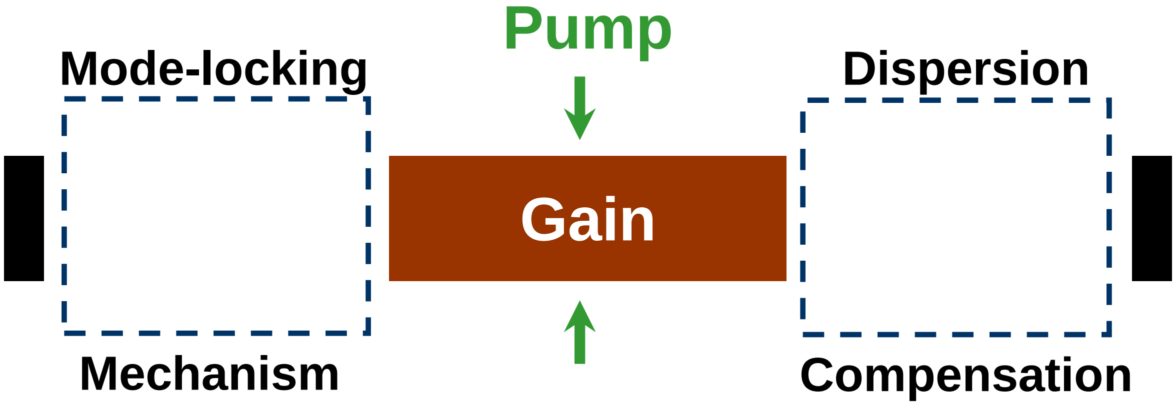
Laser output and efficiency





When the pumping power exceeds the threshold it does not increase the population inversion any longer – inversion is clamped at its threshold value. The pump power is now converted to the laser output – lasing!
The steeper the slope *(I vs Pumping rate)* the higher is conversion efficiency.

Basic principles of ultrafast (short pulse) lasers



Pump

Mode-locking

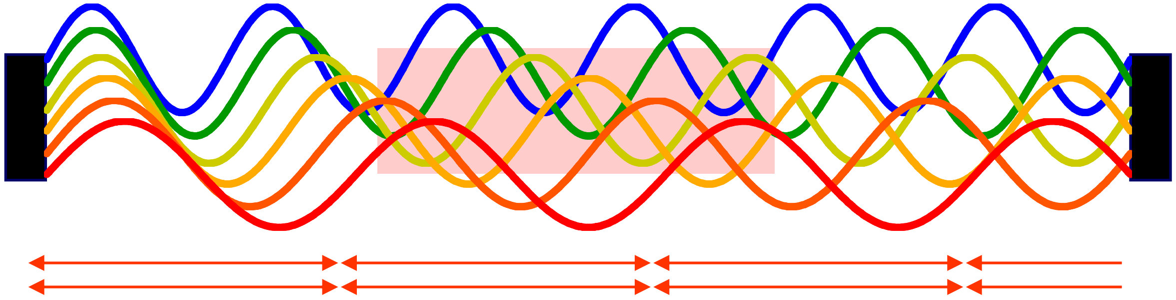
Gain

Dispersion

Mechanism

Compensation

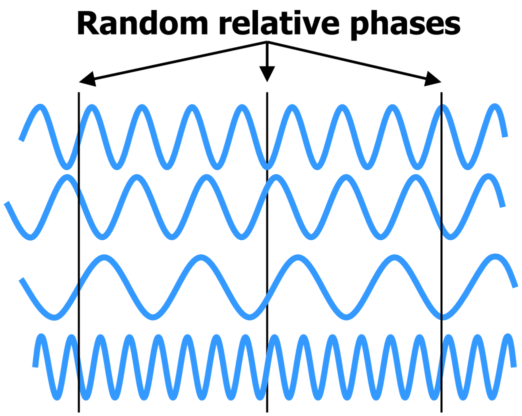
Cavity modes

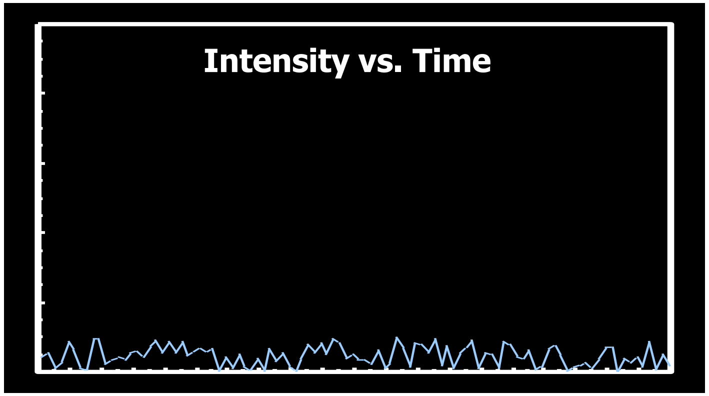


$\lambda_n = 2L/n$

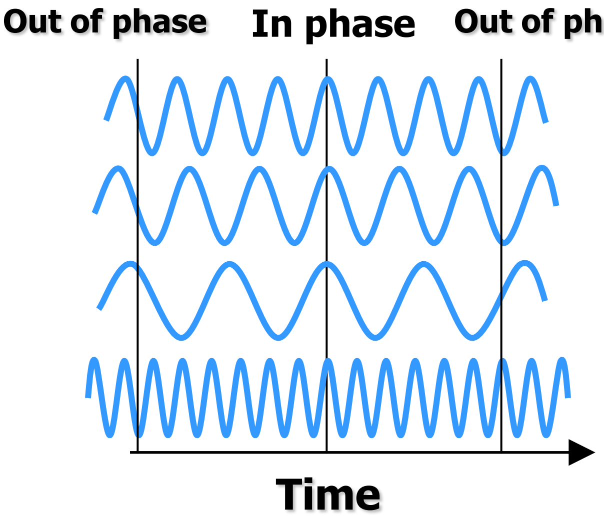
$\Delta f = c/2L$

Concept of Mode Locking

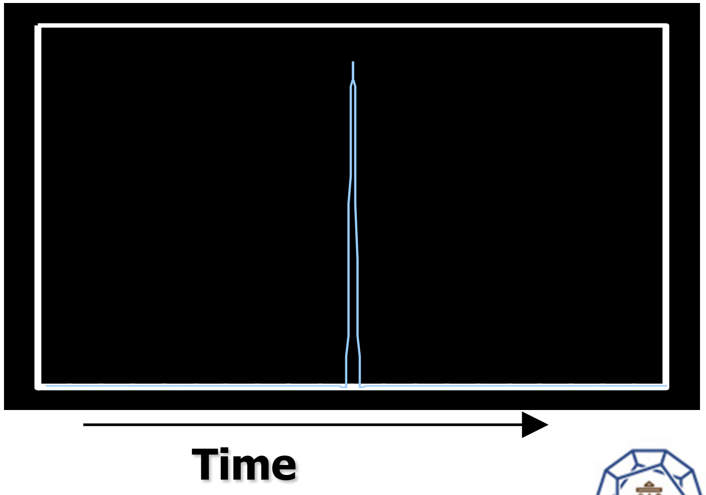




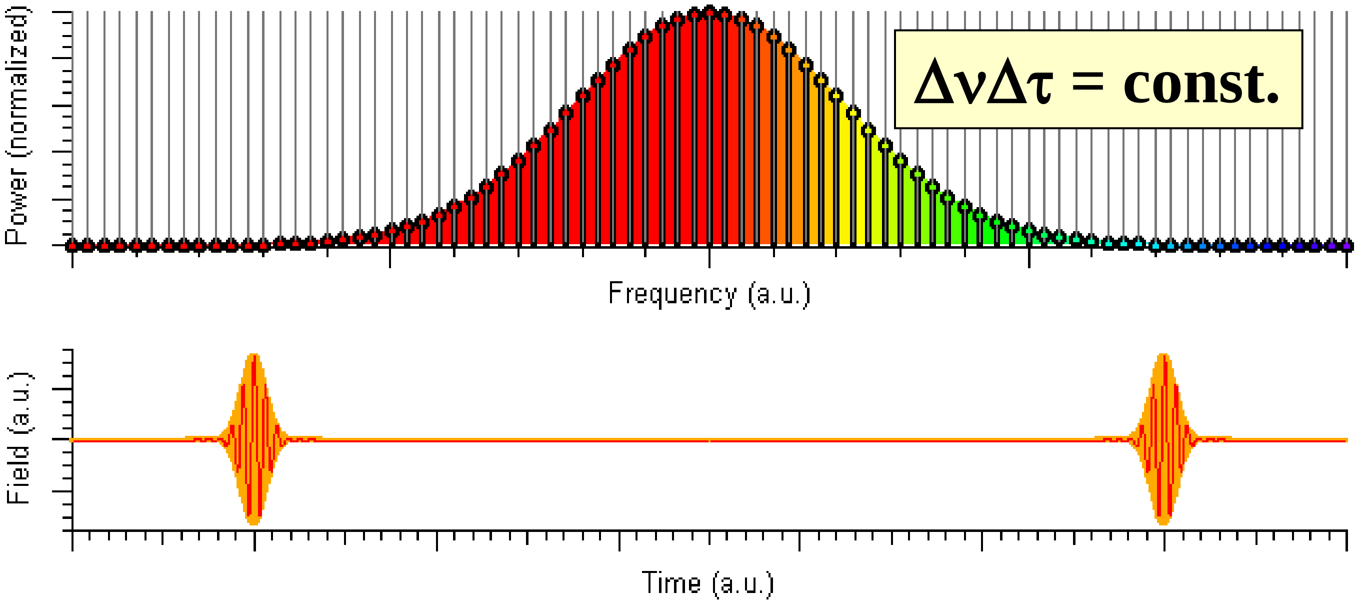
LOCKED **phases for all laser modes**



Interference **leads to pulse formation**



Bandwidth vs Pulsewidth



$\Delta\nu\Delta\tau$ = const.

Mode-locking methods

Active:

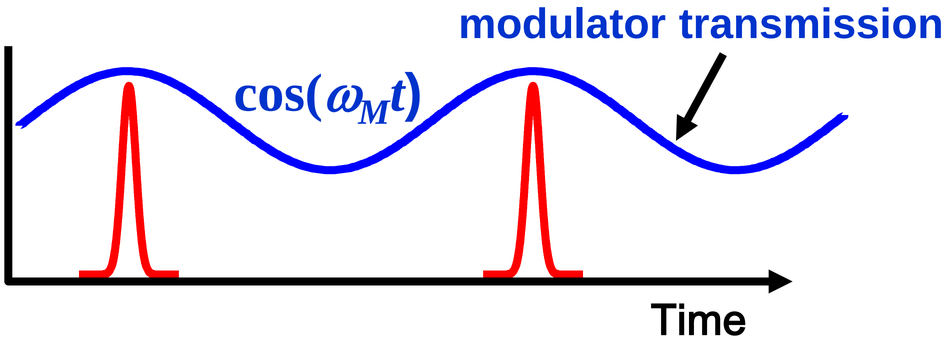
external signal to induce a modulation
of the intra-cavity light

Passive:

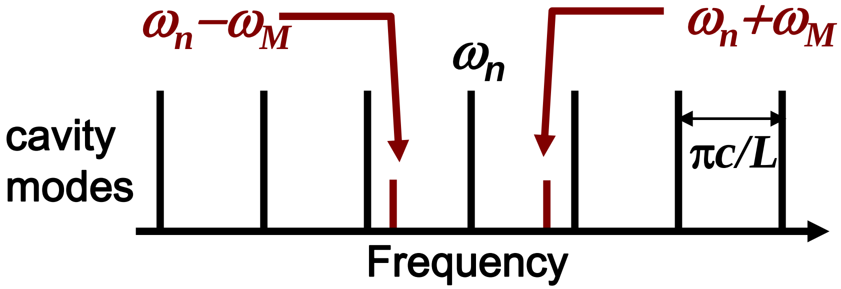
element in the laser cavity to cause
self-modulation of the light

(Shorter pulses, but has startup problems)

Active mode-mocking



In the frequency domain, a modulator introduces sidebands of every mode

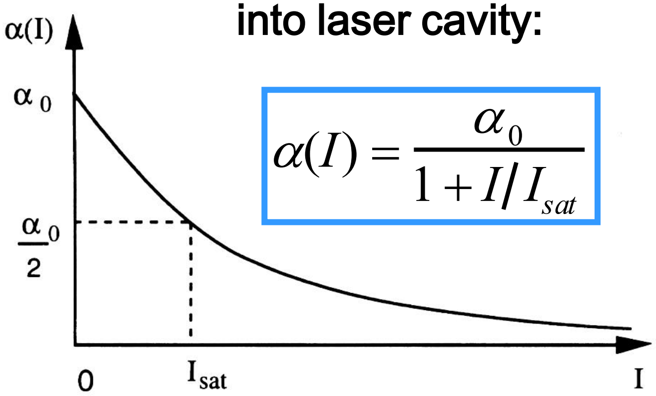


When ω_M = mode spacing, the sidebands of each mode coincide with the two adjacent modes. The sidebands and the modes compete for gain from the same atoms.
The sidebands win! so all three modes are driven in phase.
Since this applies to all N cavity modes all of them become phase locked

Can be described by N coupled equations: $E_n \Leftrightarrow E_{n+1}, E_{n-1}$

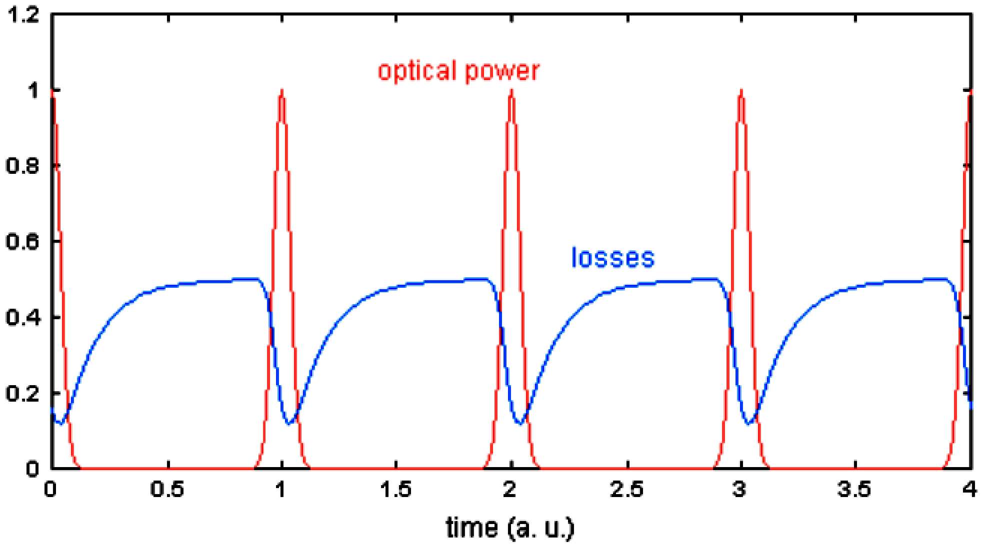
Passive mode-locking – use pulse to "gate" itself

Saturable absorption introduced into laser cavity:



$$\boxed{\alpha(I) = \frac{\alpha_0}{1 + I/I_{sat}}}$$

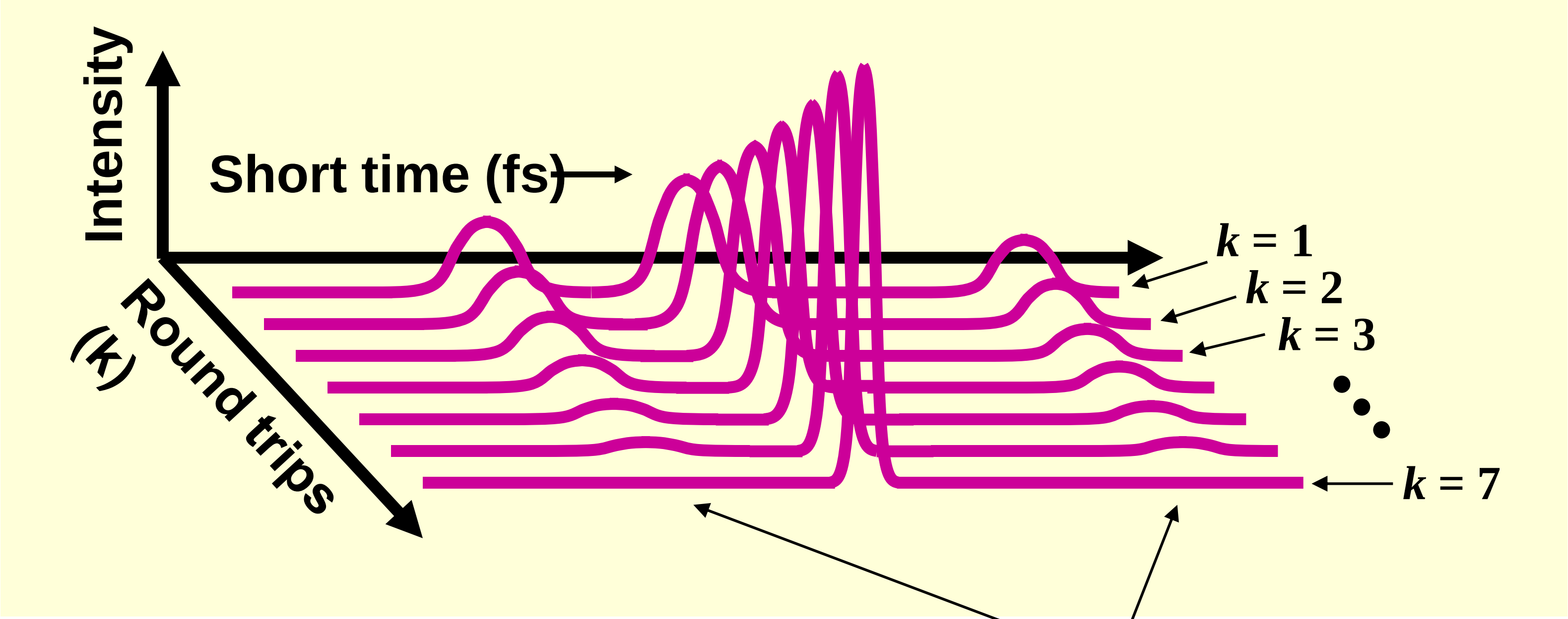
High-intensity spikes amplified -
Low-intensity light absorbed



Pulse peak amplified – pulse wings suppressed

The effect of a saturable absorber

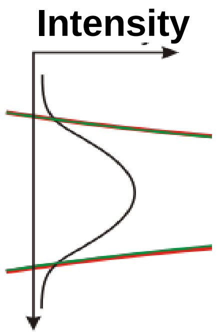
After many round trips, even a slightly saturable absorber can yield a very short pulse:

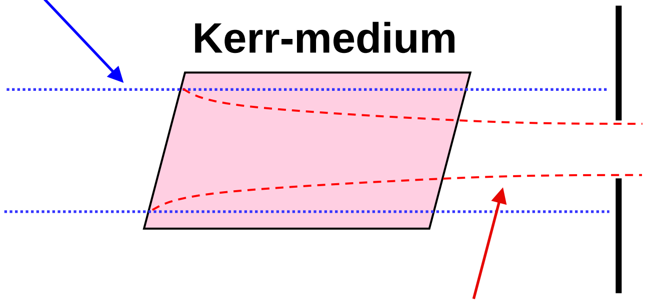


Notice that the weak pulses are suppressed, and the strong pulse shortens and is amplified

Kerr-lens modelocking (KLM)

- **Kerr's effect – intensity-dependent index of refraction: $n = n_0 + n_2 I$**
- **Beams of high-intensity modes are self-focused by the photoinduced lens**





Low-intensity

Kerr-medium

High-intensity

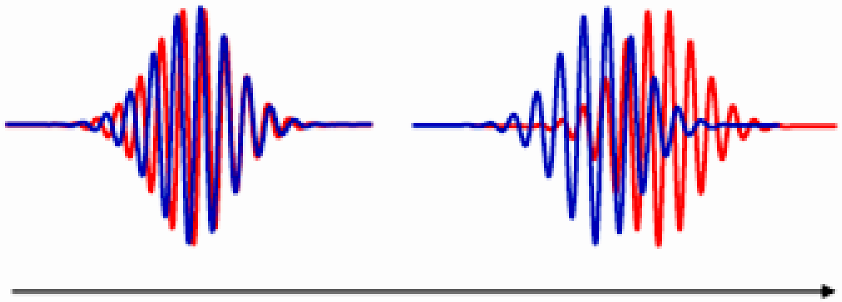
Aperture is used to discriminate unfocused low intensity modes

This acts as a saturable absorber!

Some lasing materials (e.g. Ti:Sapphire) are Kerr-media
Kerr's effect is much faster than saturable absorbers - very short pulses (~5 fs) possible

Effect of Group Velocity Dispersion

Optical pulse in a transparent medium stretches because of GVD



- $v = c / n$ – speed of light in a medium
- n –depends on wavelength, $dn/d\lambda < 0$ – normal dispersion

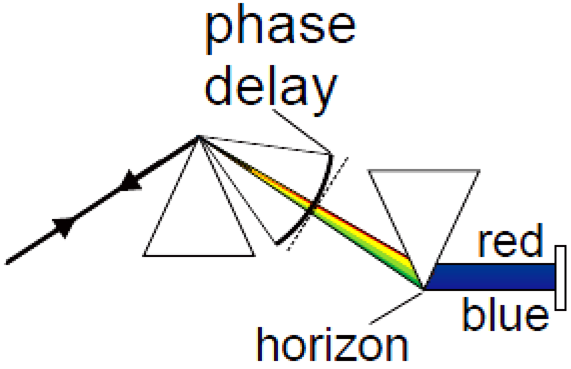
Longer wavelengths (red) of the pulse propagate faster than the shorter ones (blue)

→ **Frequency chirp** → **Pulse streching**

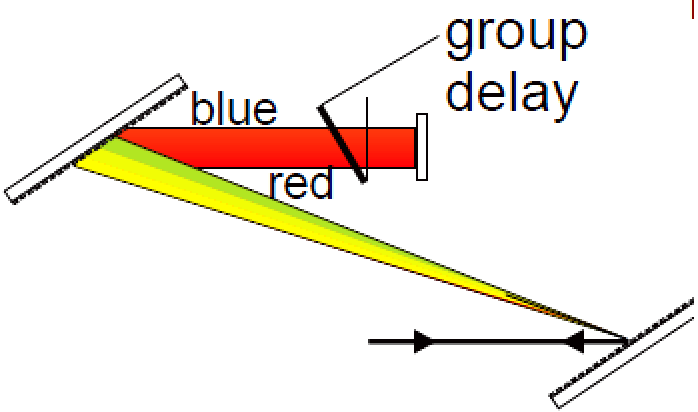
Uncompensated GVD makes fs laser operation impossible !

GVD compensation

Recompress the pulse by different optical path for different frequencies so that blue and red are in phase again:



Prism compensator

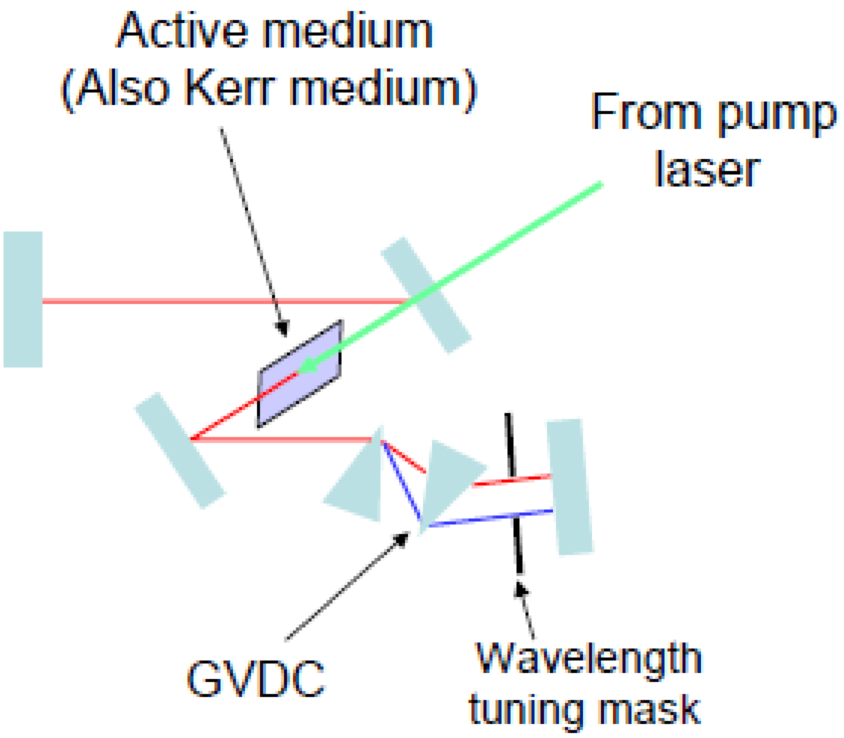


Difraction grating compensator

E.B.Treacy, *IEEE JQE* 5, 454 (1969)
Fork et al., *Opt. Lett.* 9, 150 (1984)

Ti:Spphire oscillator layout

Mode-locking due to self-focusing in Kerr medium



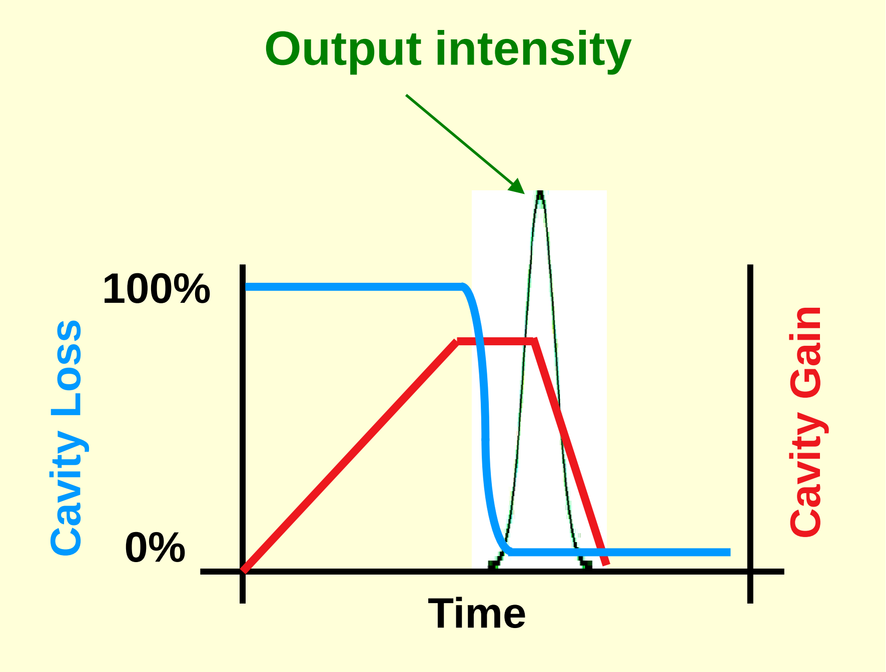
- Tuning range 690-1050 nm
- Pulse duration > 5 fs (typically 50 -100 fs)
- Pulse energy < 10 nJ
- Repetition rate 40 – 1000 MHz (determined by the cavity length)
- Pump source:
  Ar-ion laser (488+514 nm)
  DPSS CW YAG laser (532 nm)
- Typical applications:
  time-resolved emission studies, multi-photon absorption spectroscopy and imaging

O. Zvelto, “Principles of lasers”, Plenum, NY (2004)

Q-switching principle

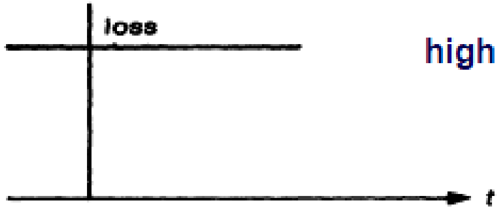
Preventing the laser from lasing until the inversion reaches its peak

Abruptly allowing the laser to lase - burst of power released in the form of pulse

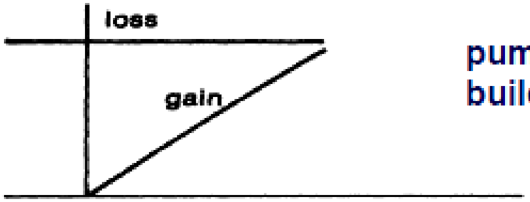


Extremely *h*igh peak-power pulses (gigawatt)
Low pulse repetition rates
Pulse length limited by the round-trip time and how fast we can switch

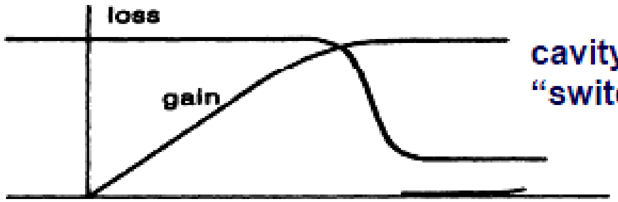
Q-switching – Giant pulse lasers



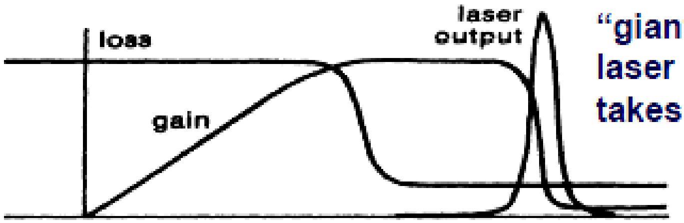
high initial cavity loss



pumping process
builds up a large inversion



cavity loss is suddenly
“switched” to low value



“giant pulse”
laser action
takes place

Pulse energy:

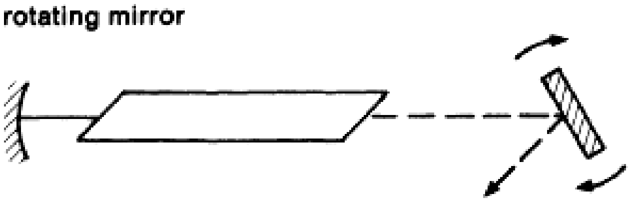
$$E \approx \Delta N_{initial} \cdot \hbar\omega$$

Pulse power:

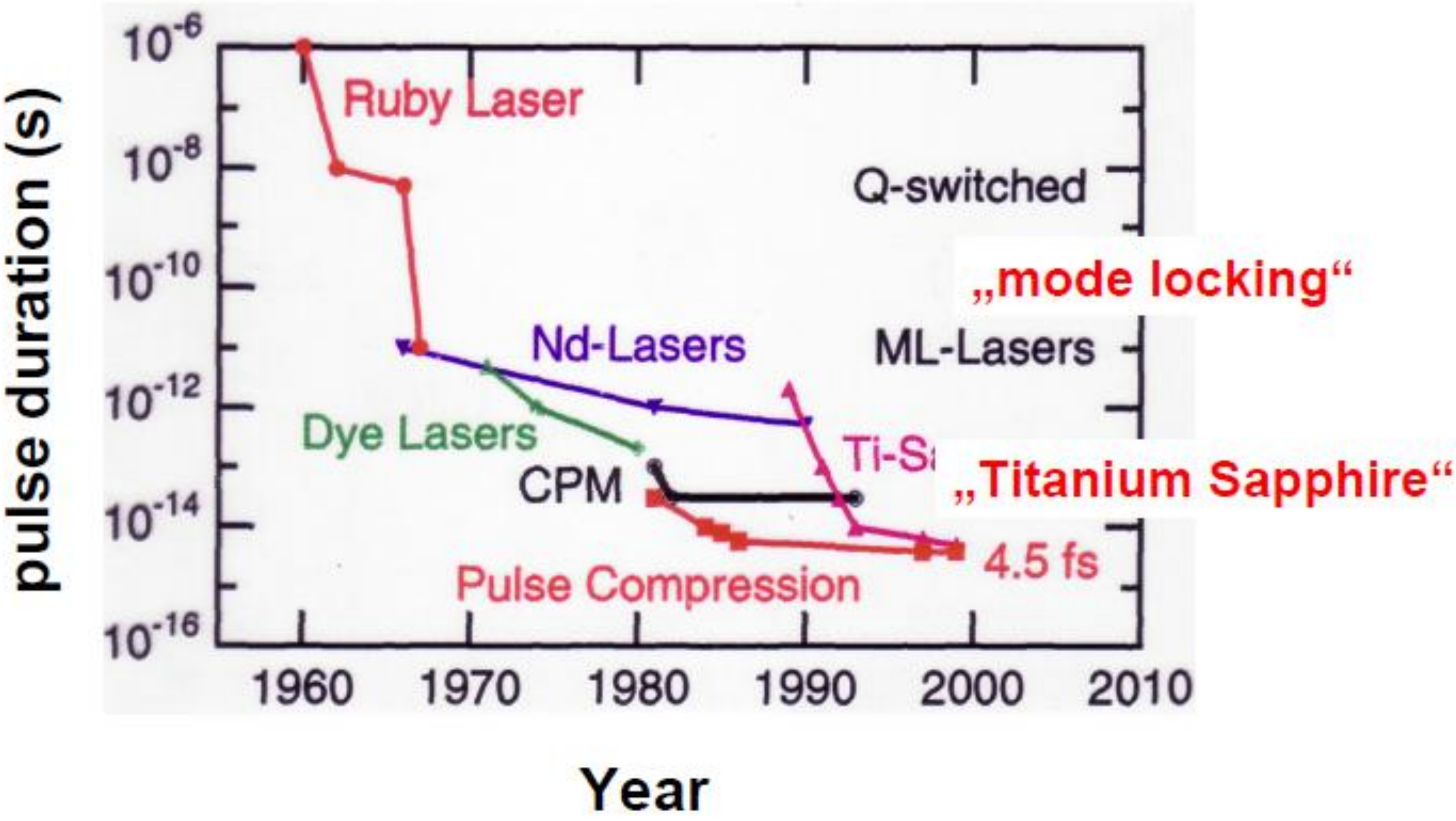
$$P \propto \frac{E}{\tau_{pulse}} \approx \frac{\Delta N_{initial} \cdot \hbar\omega}{\tau_{pulse}}$$

Typically, $P \approx 1 \div 10^3\ MW$

$$\tau_{pulse} \approx 1 \div 10\ ns$$



Development of short pulse lasers



Types of Lasers

Solid-state lasers have lasing material distributed in a solid matrix (such as ruby or Nd:YAG - neodymium:yttrium-aluminum garnet "YAG"). Flash lamps are the most common power source.

Semiconductor lasers, sometimes called diode lasers, are pn junctions. Current is the pump source.

Dye lasers use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths.

Gas lasers are pumped by current. Helium-Neon lases in the visible and IR. Argon lases in the visible and UV. CO_2 lasers emit light in the far-infrared (10.6 μm).

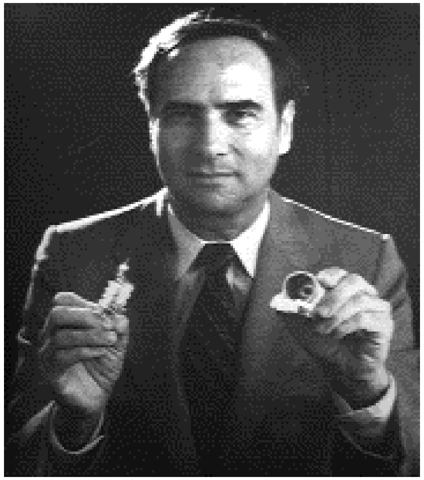
Excimer lasers (from the terms *excited* and *dimers*) use reactive gases, such as chlorine and fluorine, mixed with inert gases such as argon, krypton, or xenon. When electrically stimulated, a pseudo molecule (dimer) is produced. Excimers lase in the UV.

Fiber lasers: Optically pumped, Er-doped laser, Yb-doped laser, Raman laser.

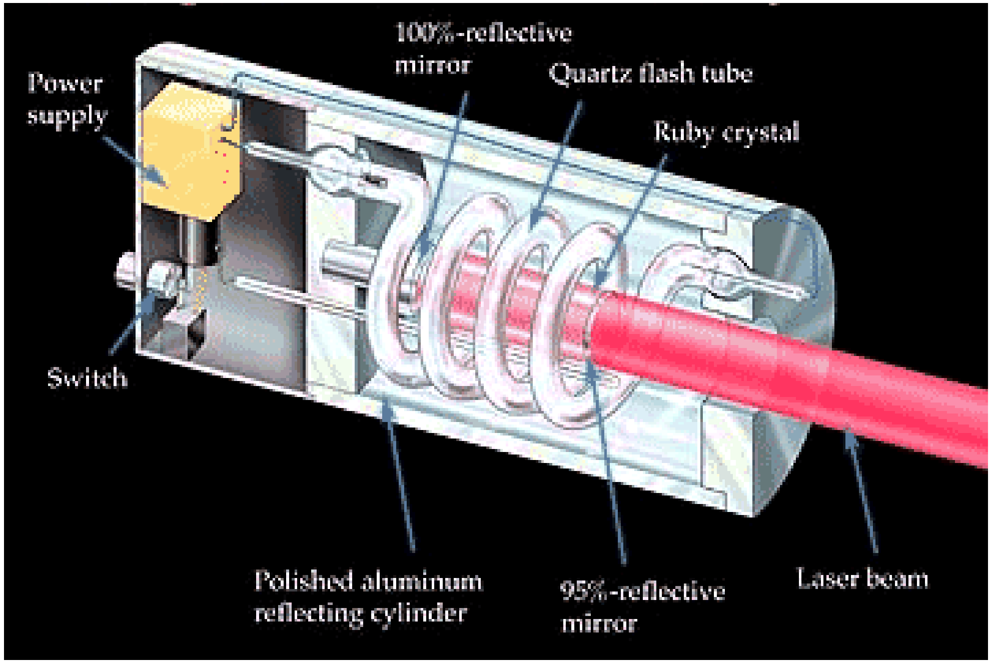
The Ruby Laser

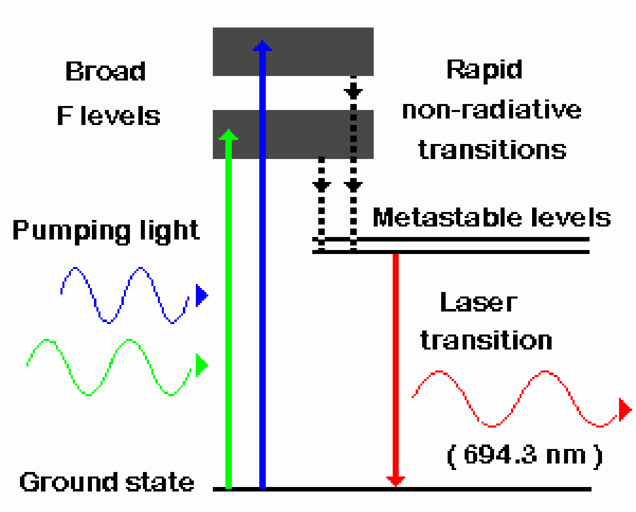
Invented in 1960 by Ted Maiman at Hughes Research Labs, it was the first laser

Photo-pumped by a fast discharge flash-lamp



1927- 2007



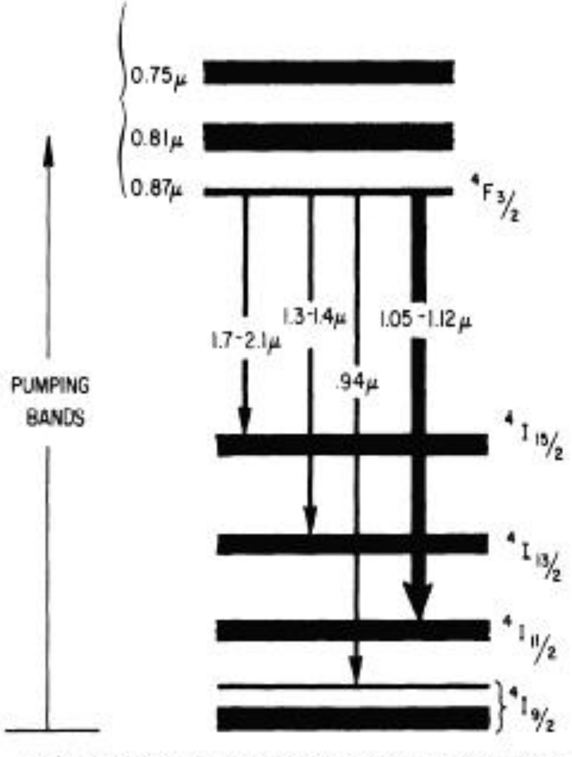


Energy levels of chromium ions in ruby

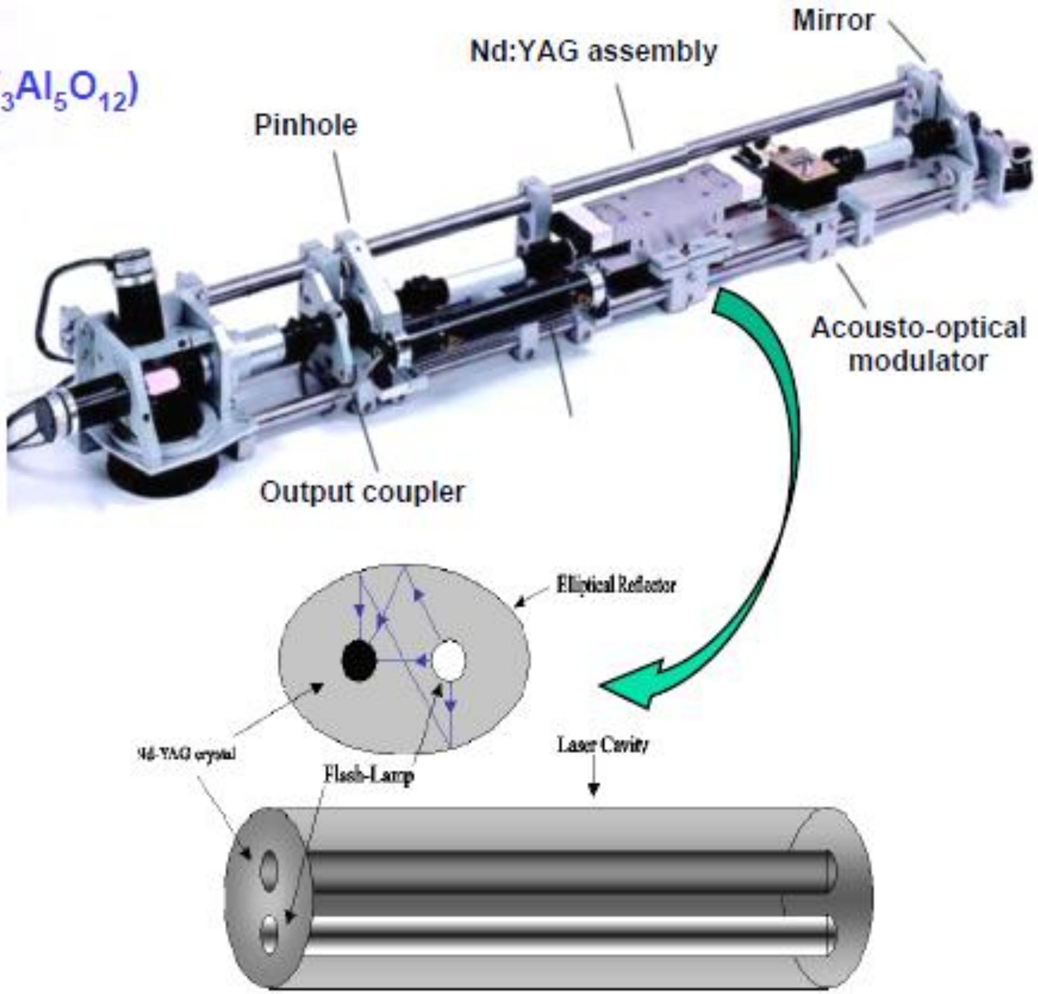
Nd:YAG laser

The trivalent neodymium ion Nd^{3+}

Lattice: yttrium aluminum garnet ($Y_3Al_5O_{12}$)

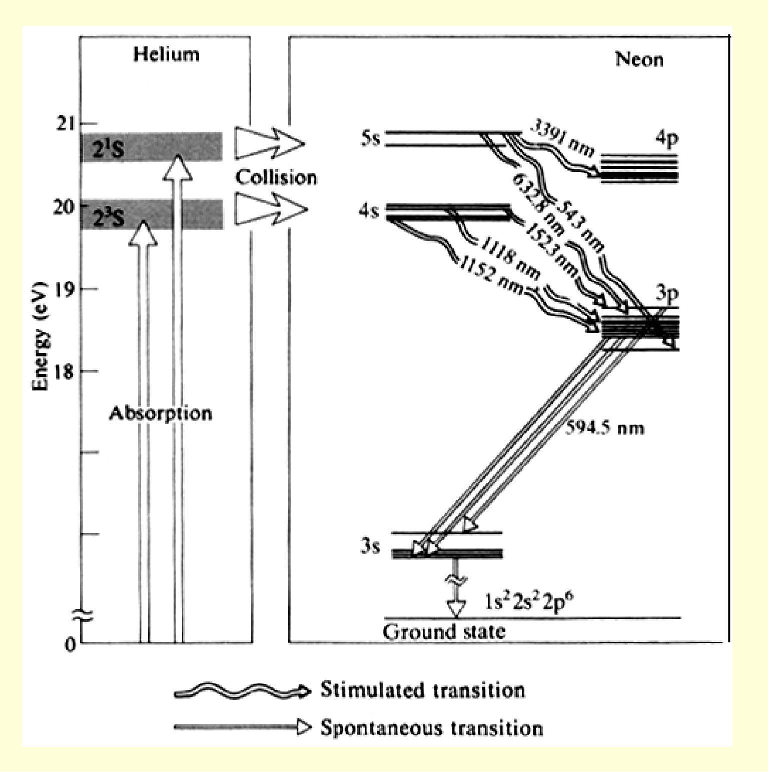


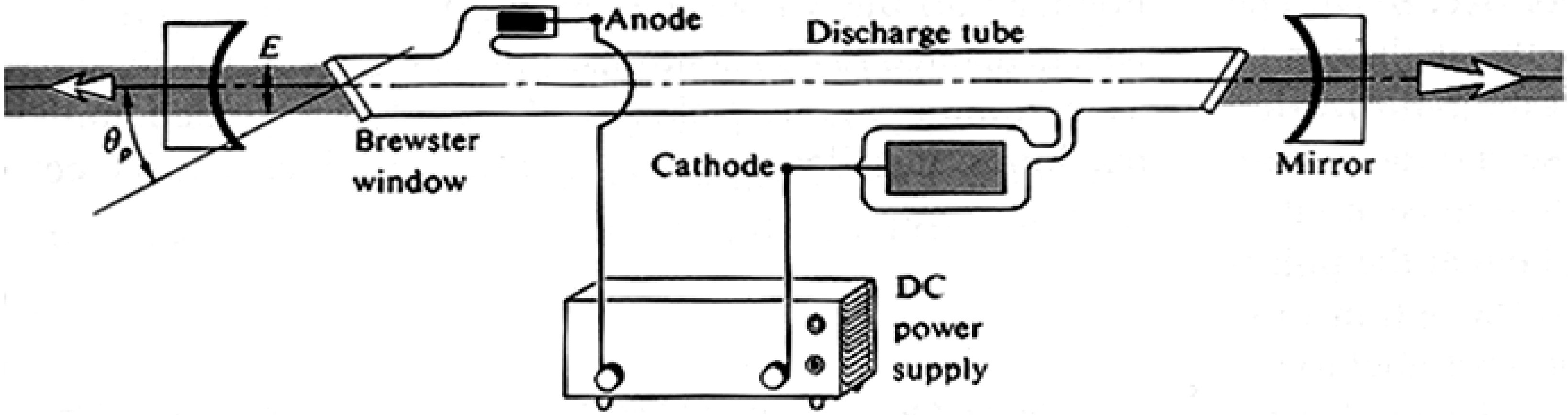
Main pump bands and fluorescent transitions in Nd:YAlG. The main laser transition is at 1.064 μ.



The Helium-Neon Laser

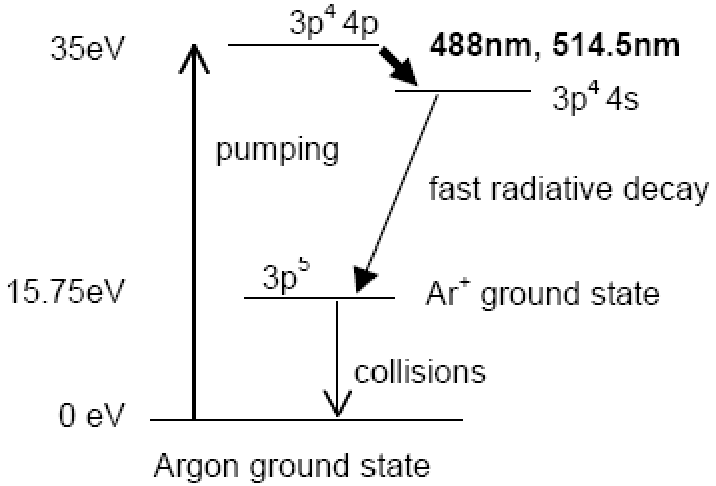
Energetic electrons in a glow discharge collide with and excite He atoms, which then collide with and transfer the excitation to Ne atoms, an ideal 4-level system.





The Argon Ion Laser

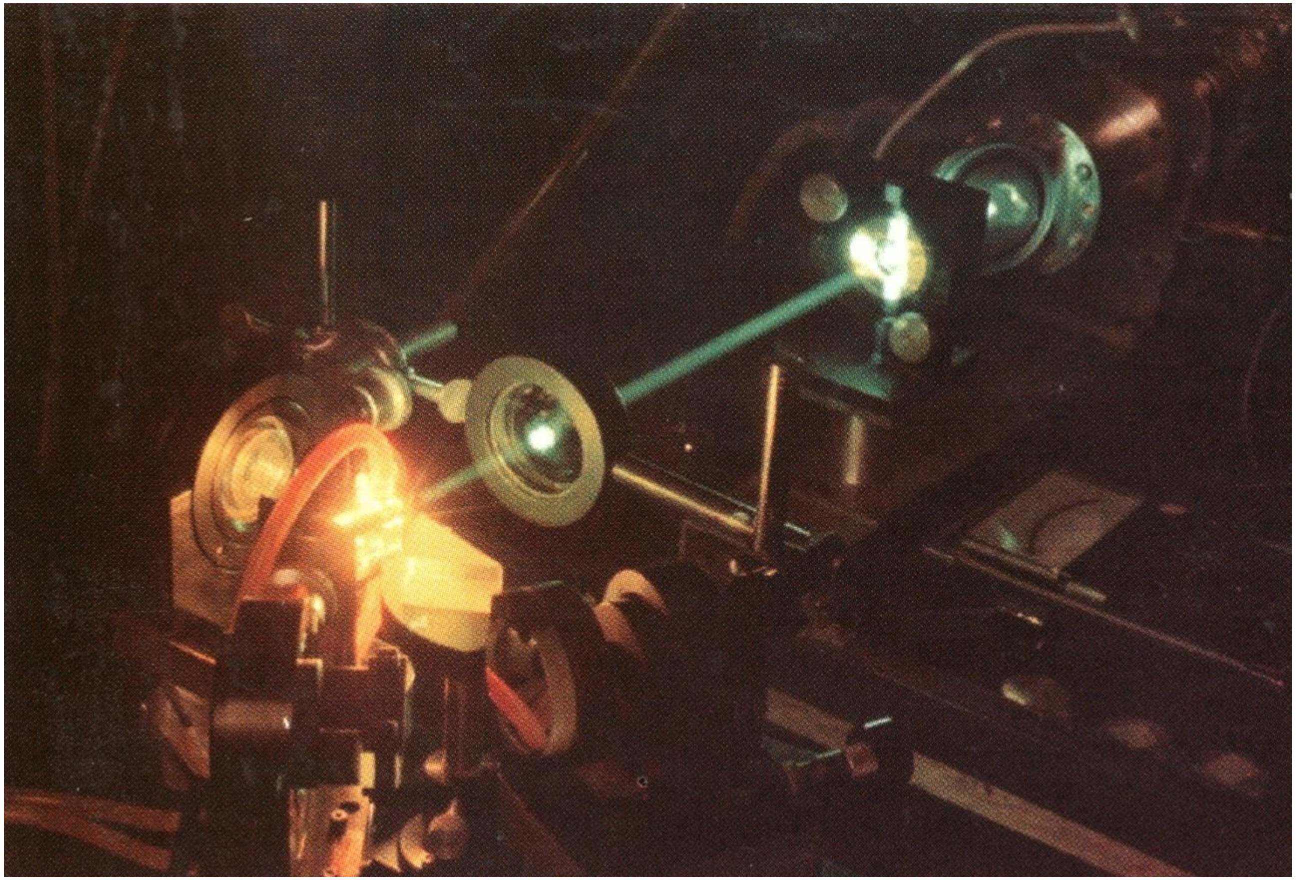
Uses ionized gas as gain mediun



Argon lines:

Wavelength	Relative Power	Absolute Power
454.6 nm	.03	.8 W
457.9 nm	.06	1.5 W
465.8 nm	.03	.8 W
472.7 nm	.05	1.3 W
476.5 nm	.12	3.0 W
488.0 nm	.32	8.0 W
496.5 nm	.12	3.0 W
501.7 nm	.07	1.8 W
514.5 nm	.40	10.0 W
528.7 nm	.07	1.8 W

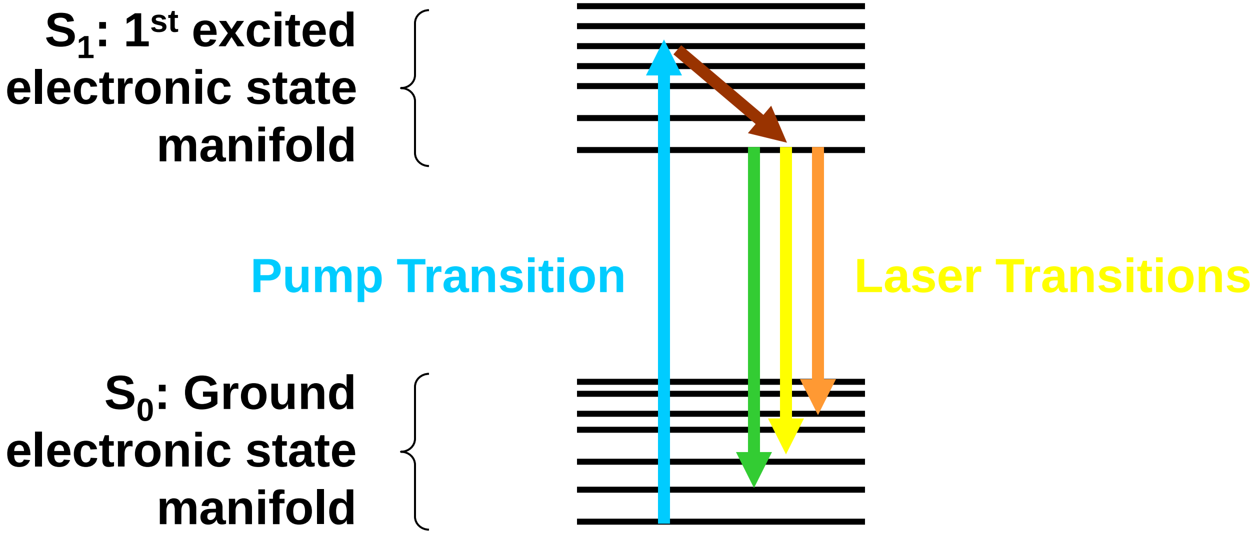
Dye lasers



Dye lasers are an ideal four-level system, and a given dye will lase over a range of ~100 nm.

A dye’s energy levels

The lower laser level can be almost any level in the S_0 manifold.



Dyes are so ideal that it’s often difficult to stop them from lasing in all directions!

Semiconductor (diode) lasers

Two outer semiconductor layers separated by a middle layer generate laser radiation when charge carriers of opposite polarity meet in the middle layer

Compact size (100µm x200 µm x50 µm)
Electrical pumping

Applications: Pump sources for solid state lasers and fiber lasers, CD player, laser printers, communications

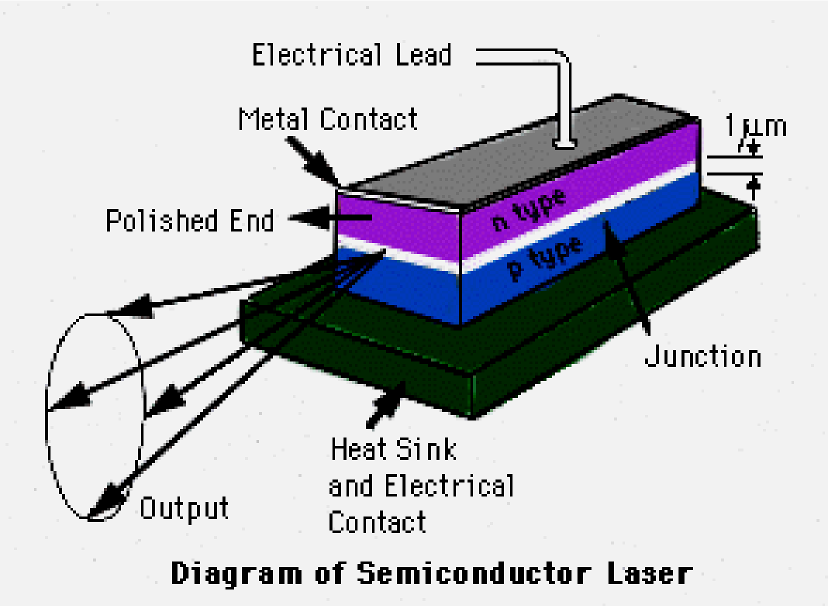
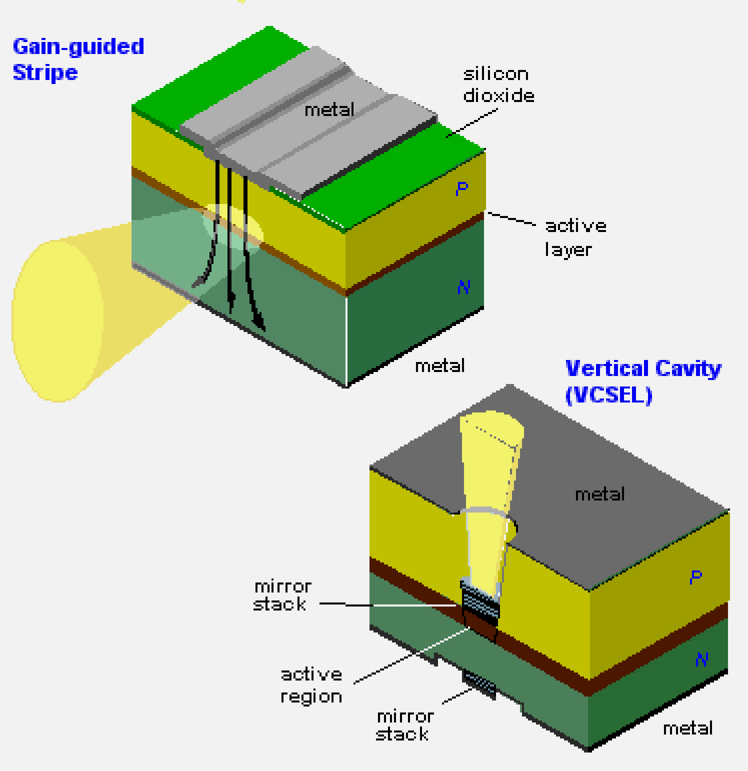


Diagram of Semiconductor Laser



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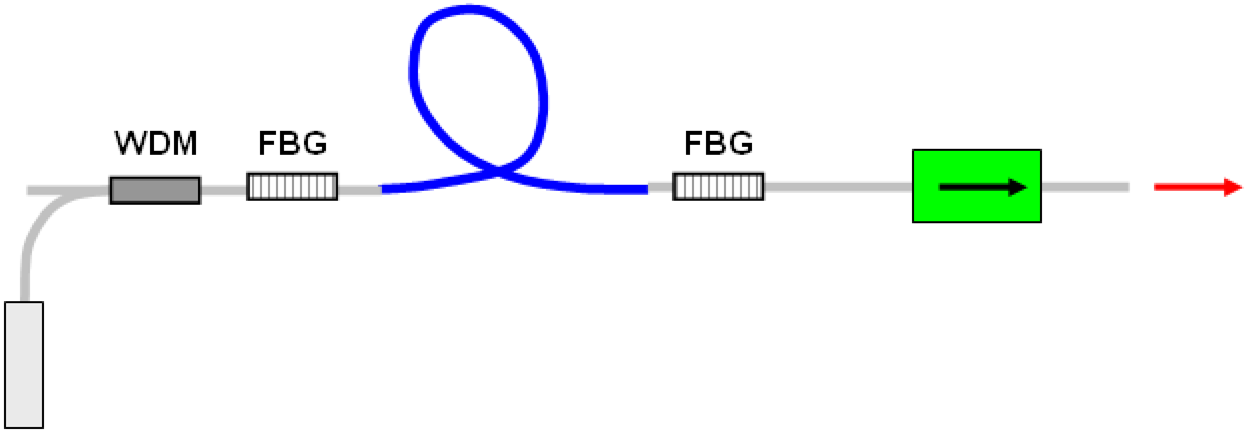
http://curie.umd.umich.edu/Phys/classes/p150/archive/goodfor/SpinFlip.htm

Fiber lasers

Active gain medium is an optical fiber doped with rare-earth elements *or utilizing fiber nonlinearities*



Scalable output power – kilowatts demonstrated (Southampton Univ)

Applications: communications, medical, material processing

Diode pumped double-clad fiber laser

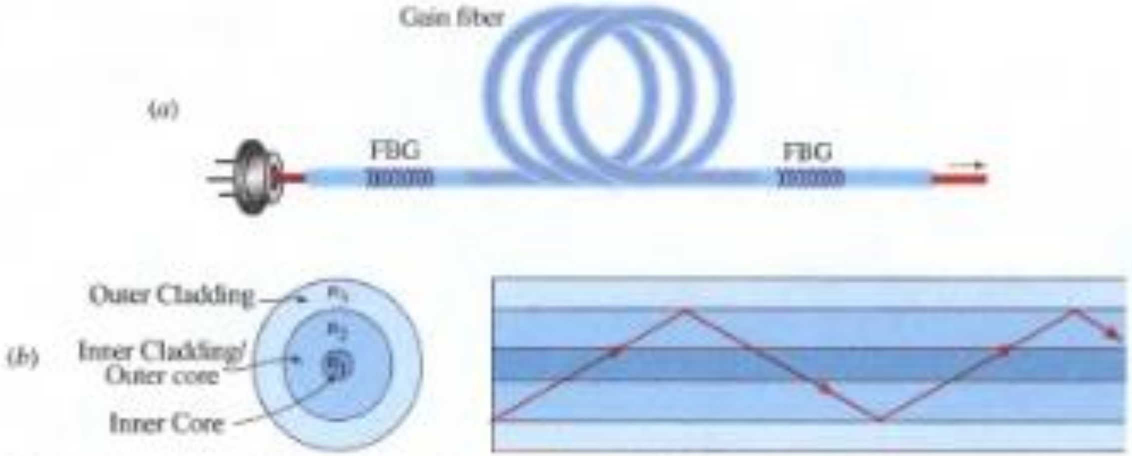


Figure 15.3-5 (*a*) Simplified schematic of a laser-diode-pumped fiber laser with fiber Bragg gratings (FBG) as reflectors. Pumping often involves multiple broad-area multimode laser diodes whose light is coupled into the outer core of the fiber via multimode couplers, in both the forward and backward directions. A single-mode inner core fosters single-transverse-mode oscillation. Fiber-laser operation has been achieved in many other configurations. (*b*) Concentric double-clad fiber configuration. Other double-clad configurations are designed to provide increased overlap between the inner core and the skew rays of the outer core (see Fig. 9.1-2). For example, the inner core may be shifted off-center (toward the edge of the outer core), or the outer core may be rectangular, hexagonal, octagonal, or D-shaped.

Properties of laser light

Directivity

At the Moon (384,400 km away) laser beam has a diameter of 3 km

Monochromaticity

The spectral width may be as narrow as 1 Hz (carrier frequency 10^{15} Hz)

Brightness

Power of light from a 100-W bulb passed through a 2-mm pinhole, at a 1-m distance, is only 0.05 mW while a CD player laser yields 5 mW

Focusability

Laser light can be focused to a spot of a size of the wavelength (~0.5 μm)

Energy Density

A 10^{13} W (10 TW) laser focused to 10 μm^2 produces the electric field of $5x10^{12}$ V/cm (Coulomb filed in the atom is $\sim 5x10^{9}$ V/cm)

Ultrashort Pulses

Pulses as short as 250 as (1 attosecond = 0. 000 000 000 000 000 001 s) have been generated