LASERS

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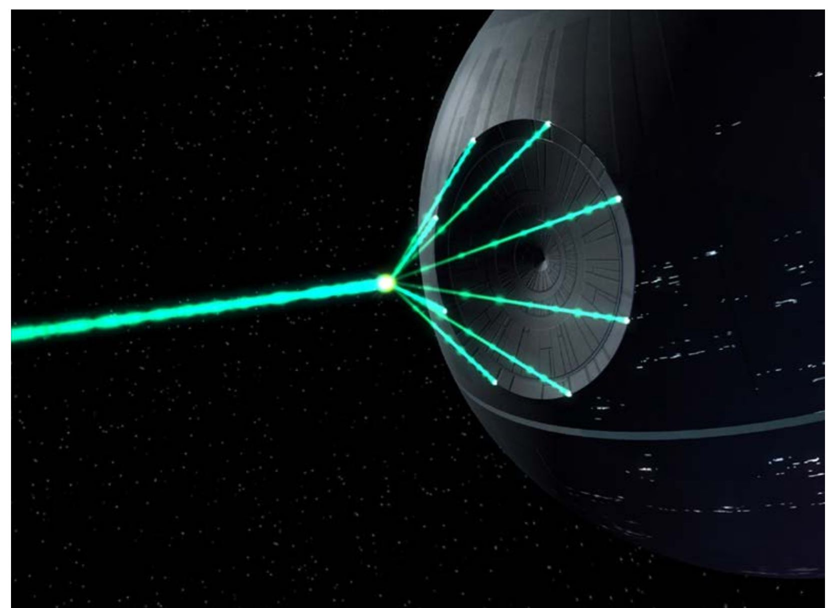
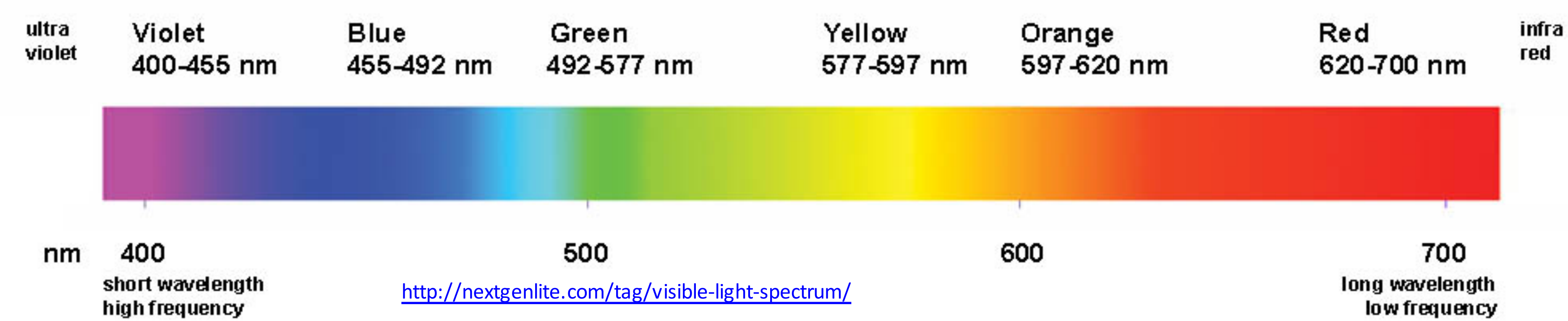
- Building blocks of laser physics
- How a laser works
- Lasers in microscopy
- Throwing stones

Truth or myth?



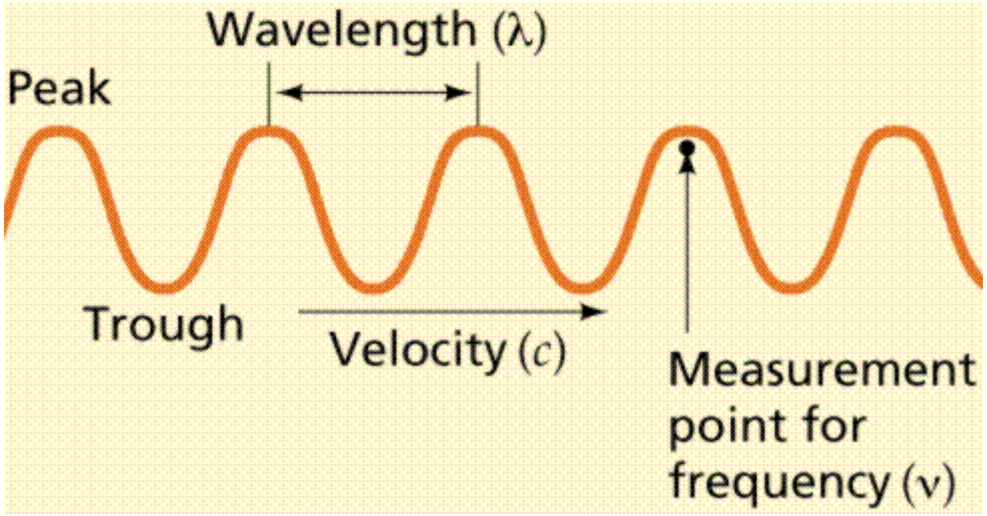
Wave nature of light



http://nextgenlite.com/tag/visible-light-spectrum/

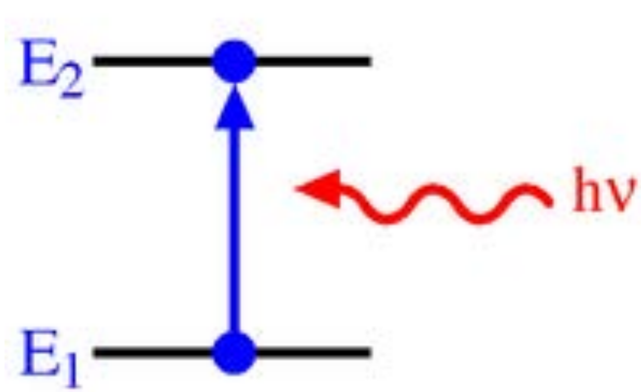
Frequency (ν)
Wavelength (λ), ranging from
Speed of light in vacuum (c)
= 3 x 10^8 m/s

$$\nu = \frac{c}{\lambda}$$

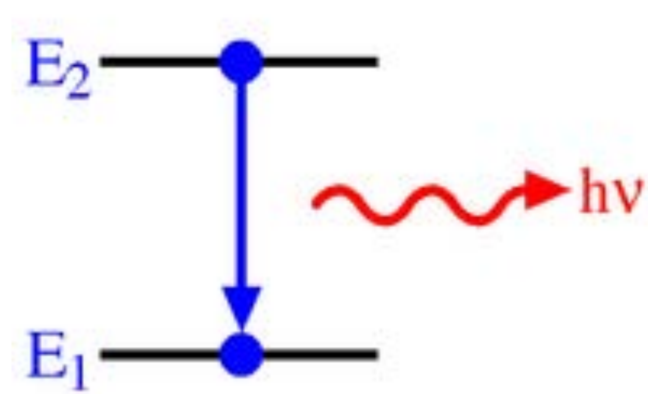


Quantum mechanics basics of lasers

1. There are discrete energy levels an atom can be at
2. The lowest and most stable energy state is the ‘ground state’
3. Discrete packets of energy ($E_2 – E_1$) can be absorbed bringing an atom from one energy level to the next.
4. Similarly, discrete packets of energy ($E_2 – E_1$) can be emitted (photons)



absorption



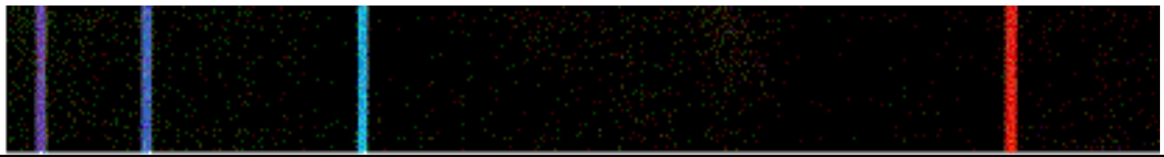
emission

http://en.wikipedia.org/wiki/Energy_level

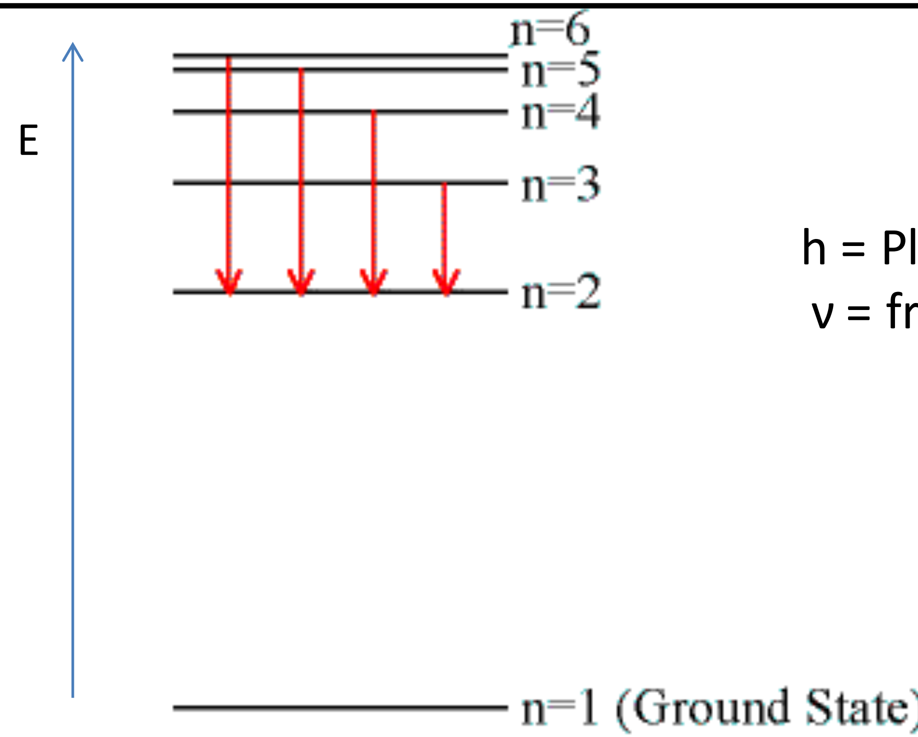
Energy levels in atoms/molecule dictate spectrum of emission

410 nm 434 nm 486 nm 656 nm

hydrogen



Which energy transition is responsible for each of these lines?



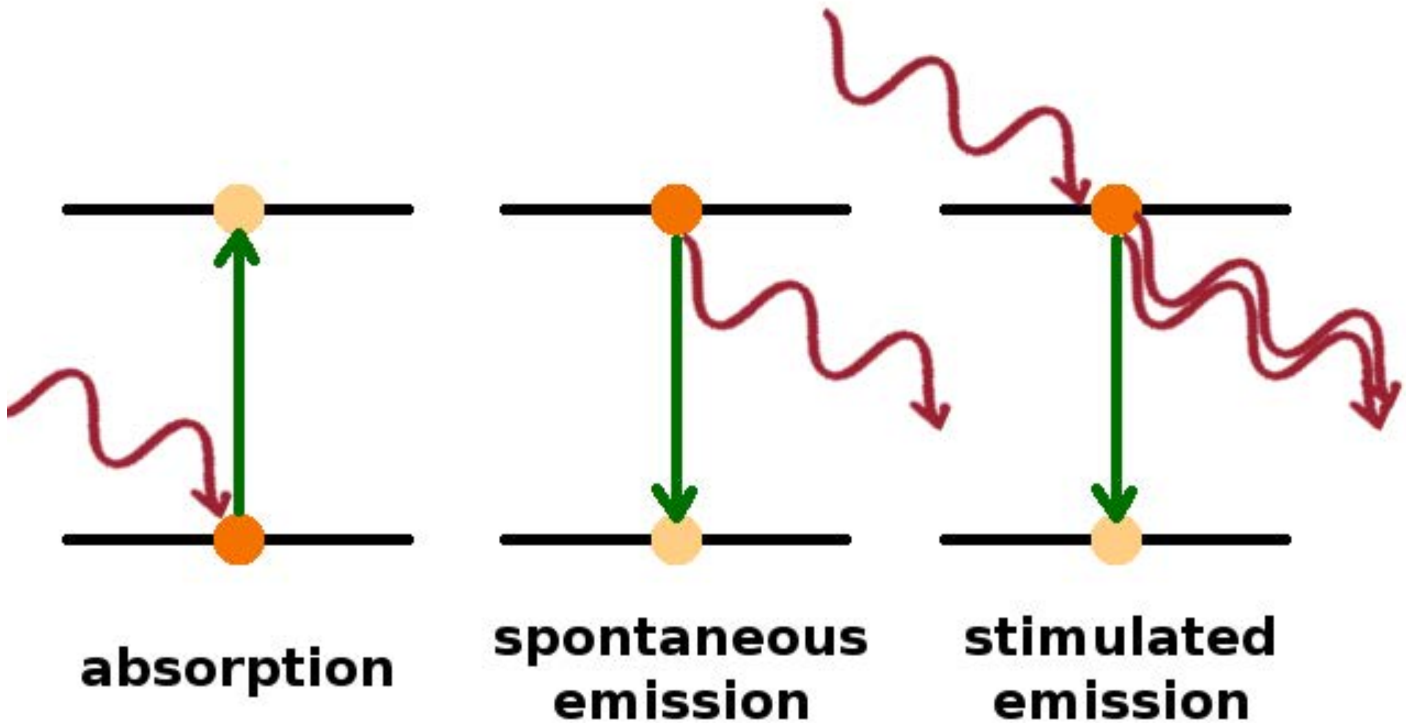
$E = h\nu$

h = Planck's constant,

ν = frequency of light

http://electron6.phys.utk.edu/phys250/modules/module%203/hydrogen_atom.htm

Stimulated emission



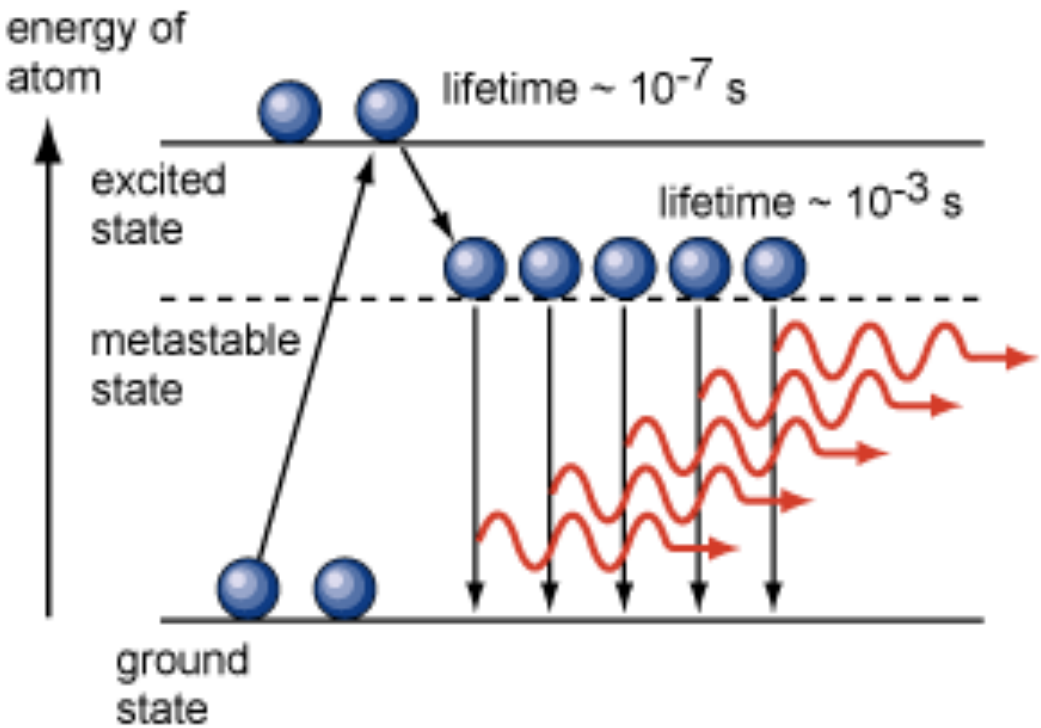
Emitted photon is of the same energy (frequency) and phase (coherent!) as the stimulating photon.

Population inversion

- More atoms in the elevated energy state

$$\frac{N_2}{N_1} > 1$$

- How do we get enough of these photons to be at that high, unstable energy level?



http://www.hk-phy.org/articles/laser/laser_e.html

Light

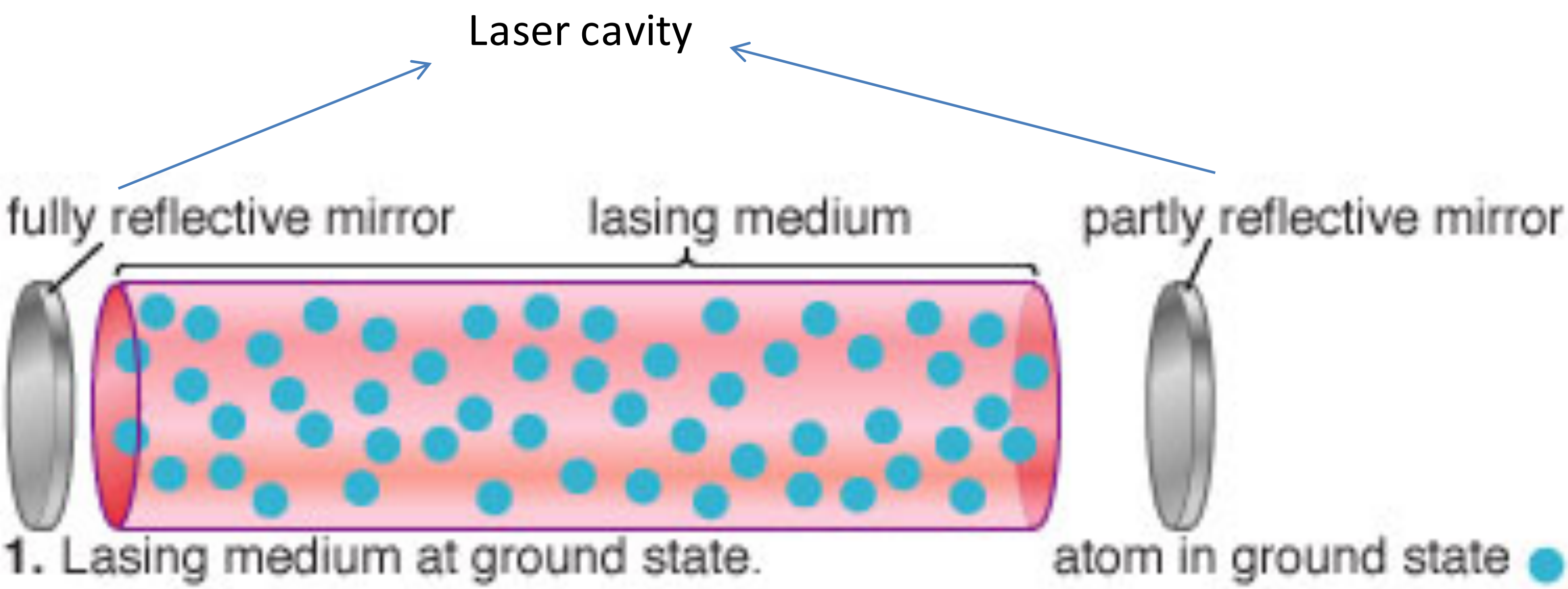
Amplification by the

Stimulated

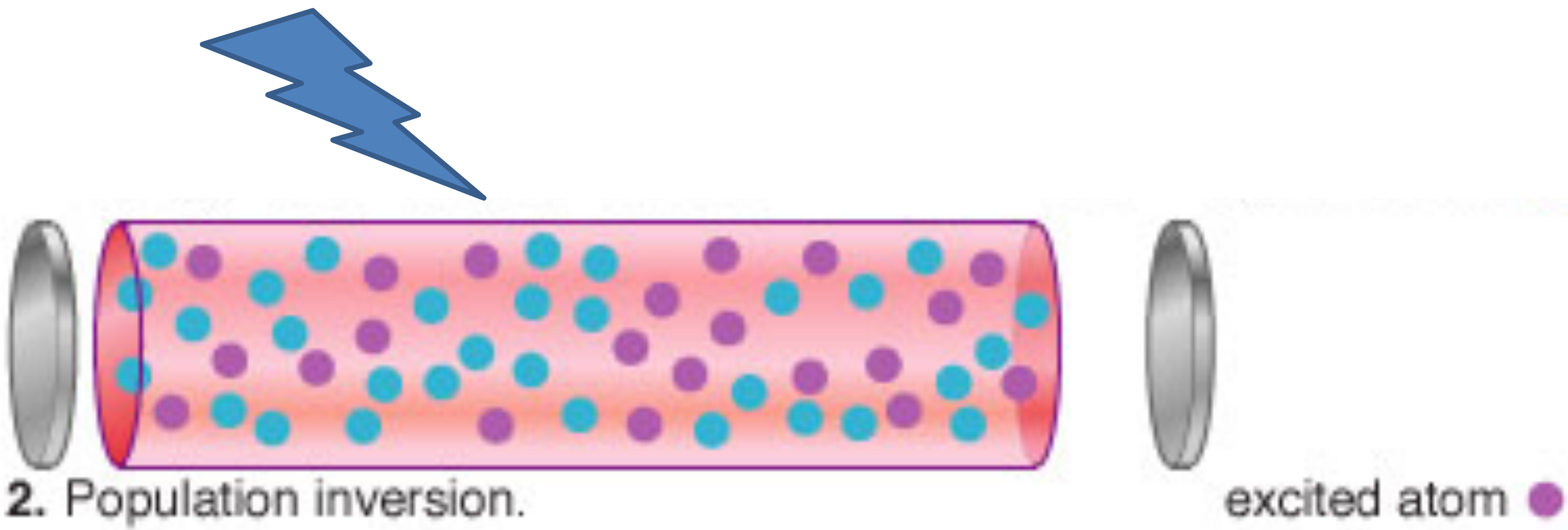
Emission of

Radiation

1. Laser at ground (off) state



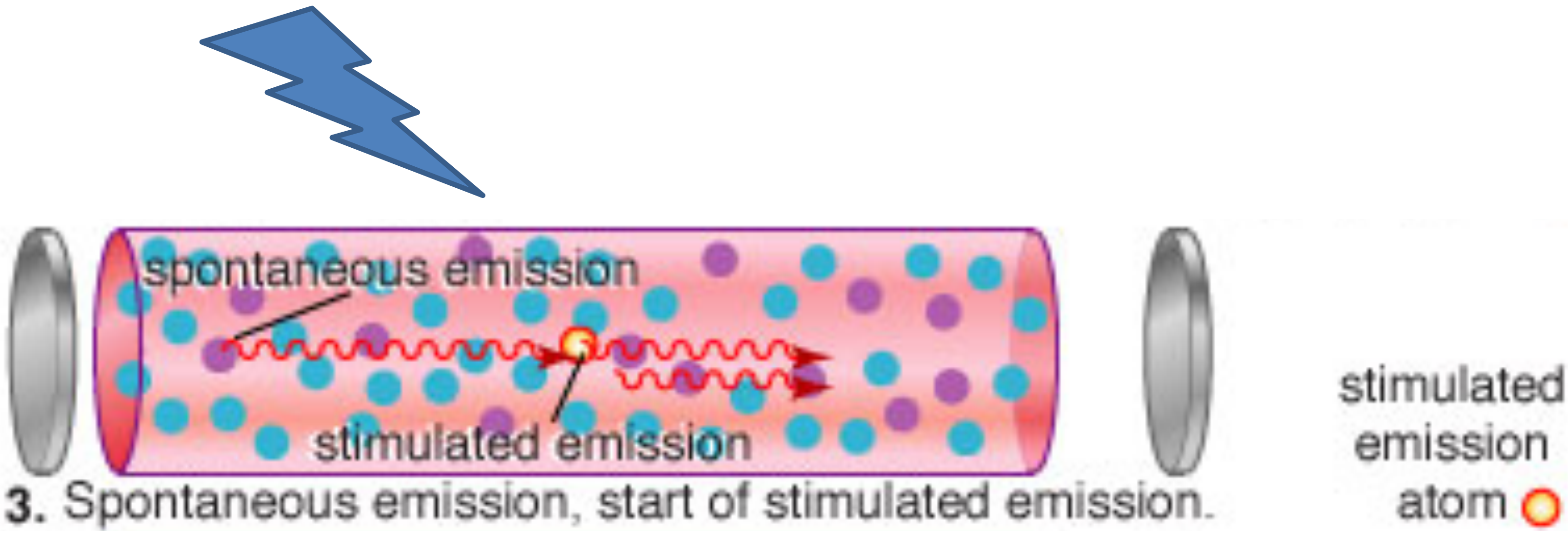
2. Pumping



Pumping: energy input for stimulated absorption

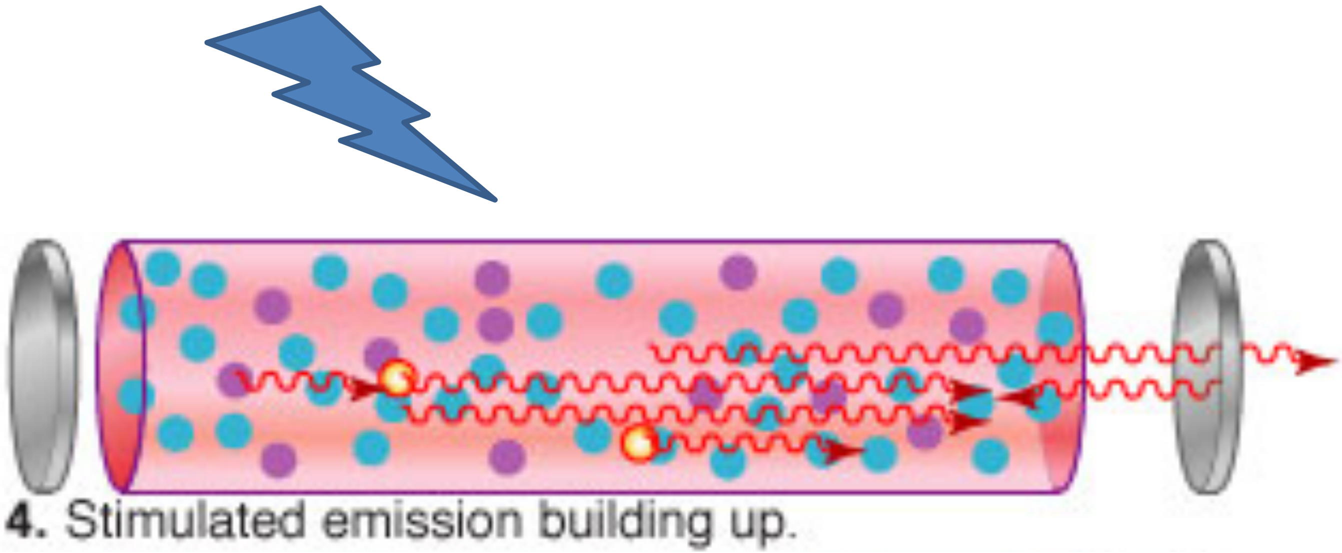
Lasing medium can be pumped either electrically or by another light source

3. Spontaneous emission: start of chain reaction



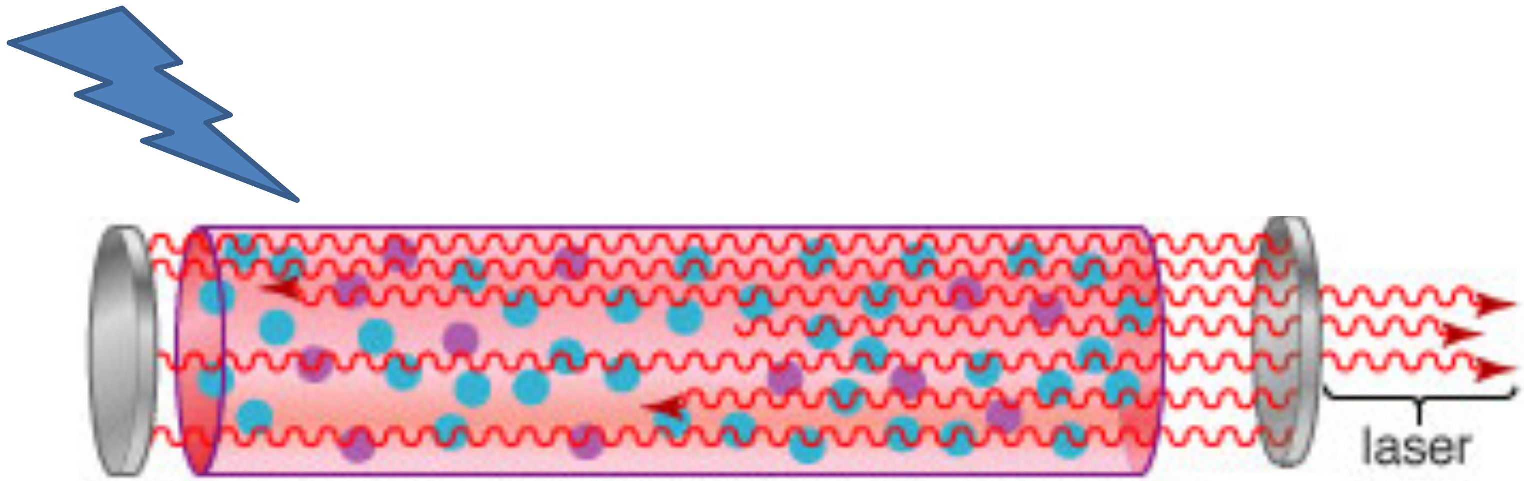
Spontaneously emitted photon causes stimulated emission

4. Emitted photons stimulate emission of more photons



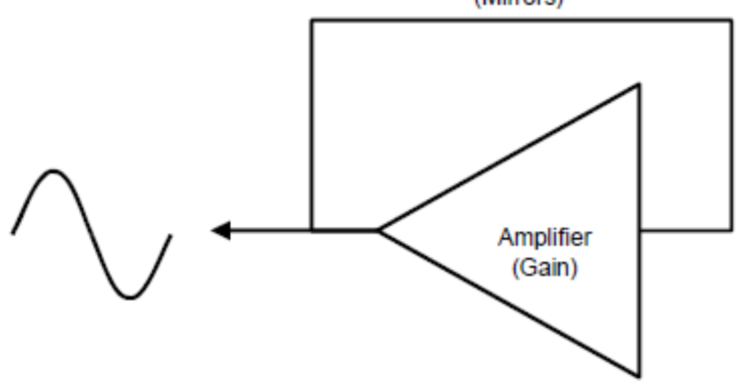
Emitted photons have the same frequency and phase!

5. Lasing at equilibrium

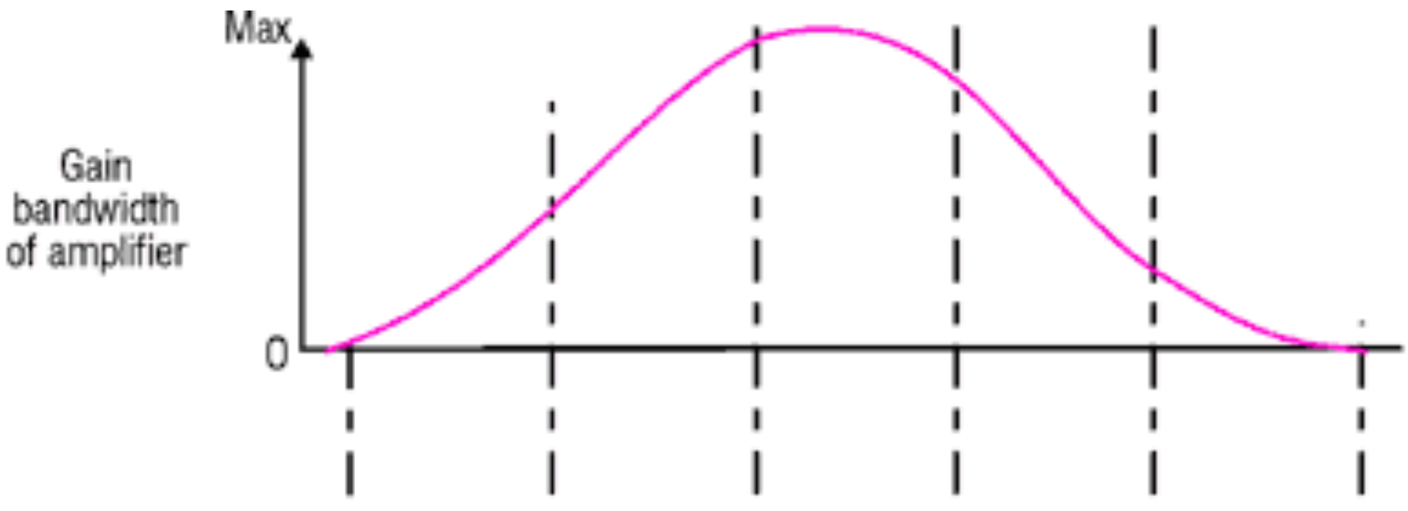


5. Coherent light, with all waves lined up in phase.

Laser is analogous to an oscillator

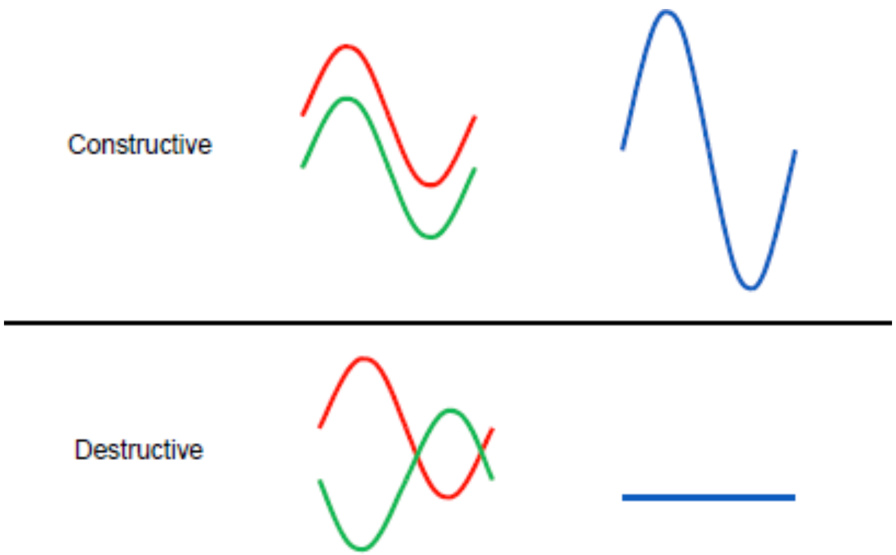


“Gain bandwidth” of laser is broad

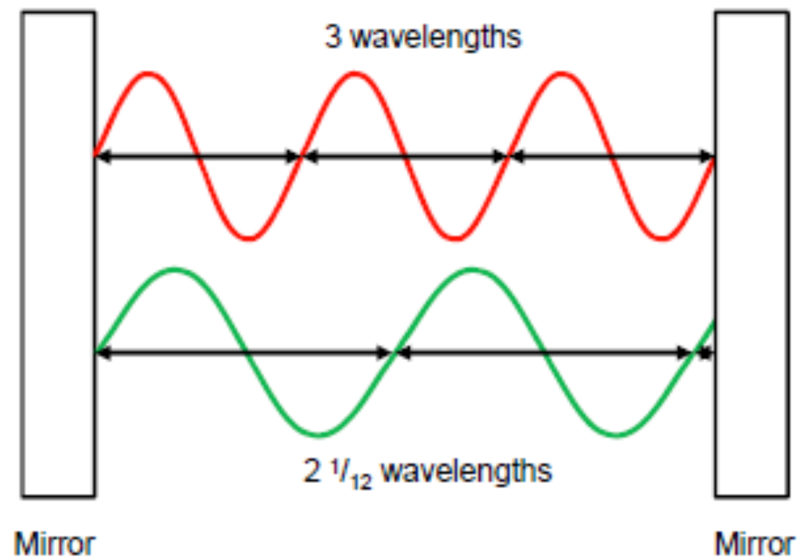


Many wavelengths are possible
How do we select for just a few?

Constructive & destructive interference



Stolen from Scott



Completely constructive interference occurs when cavity length is integer multiples of wavelength

$$N \cdot \lambda = 2 \cdot L$$

N is an integer, **λ** is the wavelength,

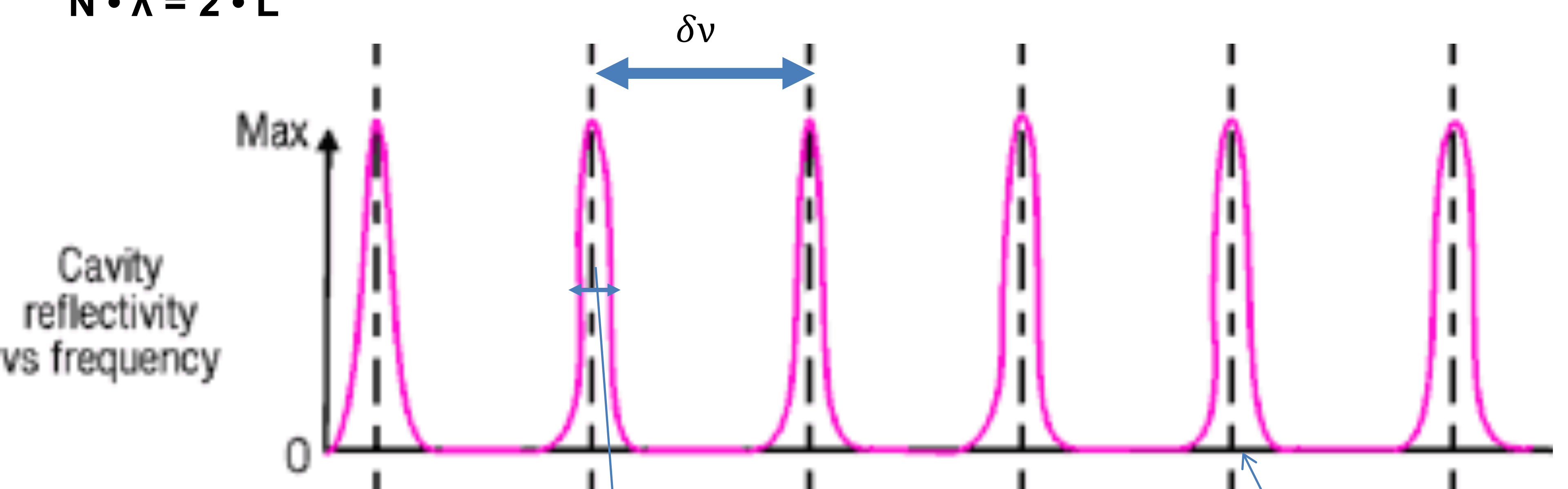
L is laser cavity length.

Resulting transmission characteristic of laser cavity

“free spectral range”

$$\delta\nu = \frac{c}{n \cdot L}$$

N • λ = 2 • L

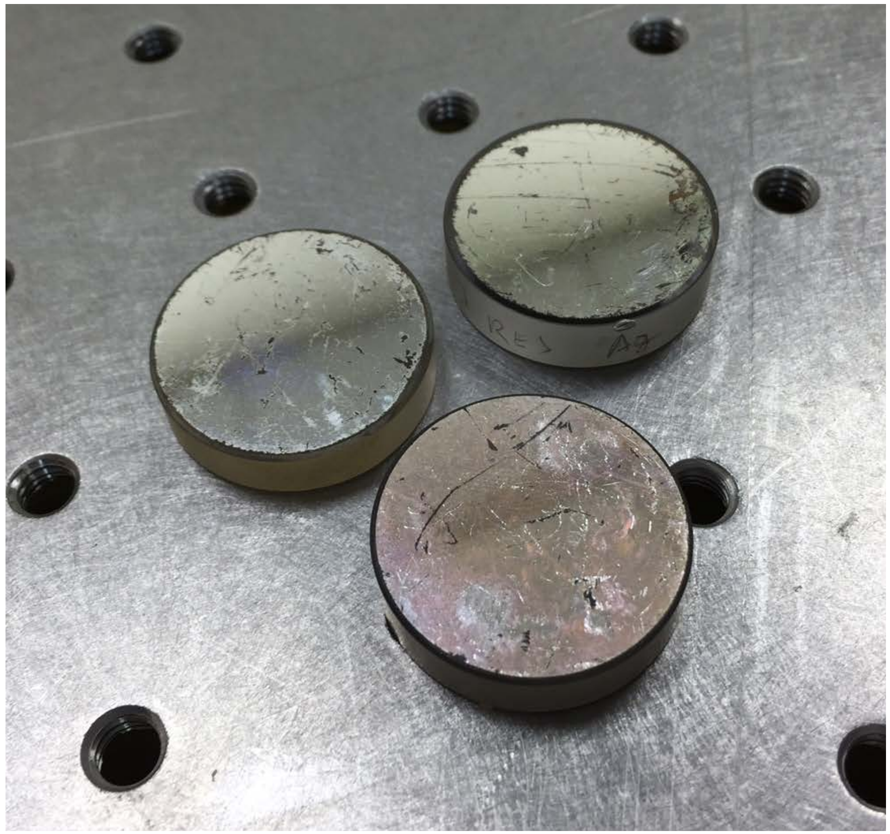


Optical frequency

Longitudinal mode

‘finesse’, related to quality and reflectivity of the mirrors

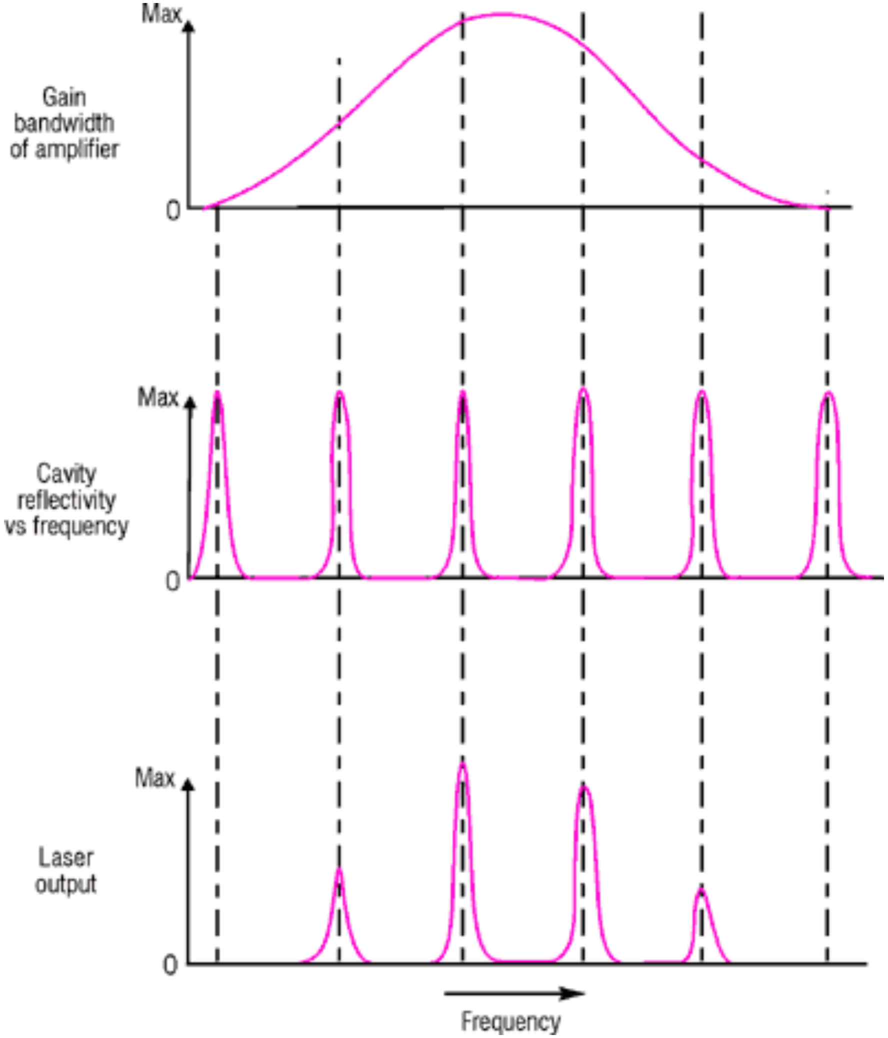
Resulting transmission characteristic of laser cavity



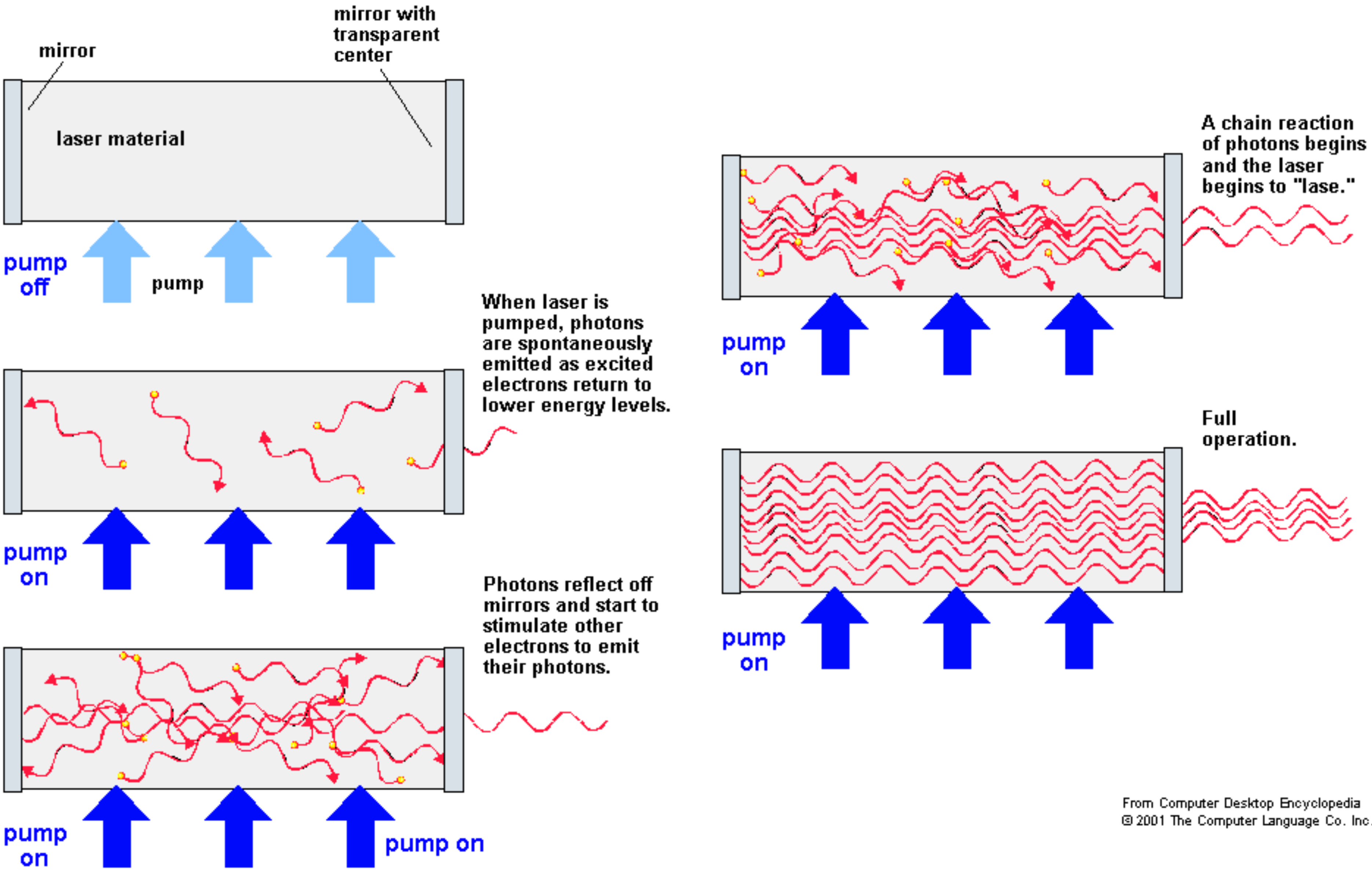
‘finesse’, related to quality and reflectivity of the mirrors

Resulting laser spectra

$N \cdot \lambda = 2 \cdot L$

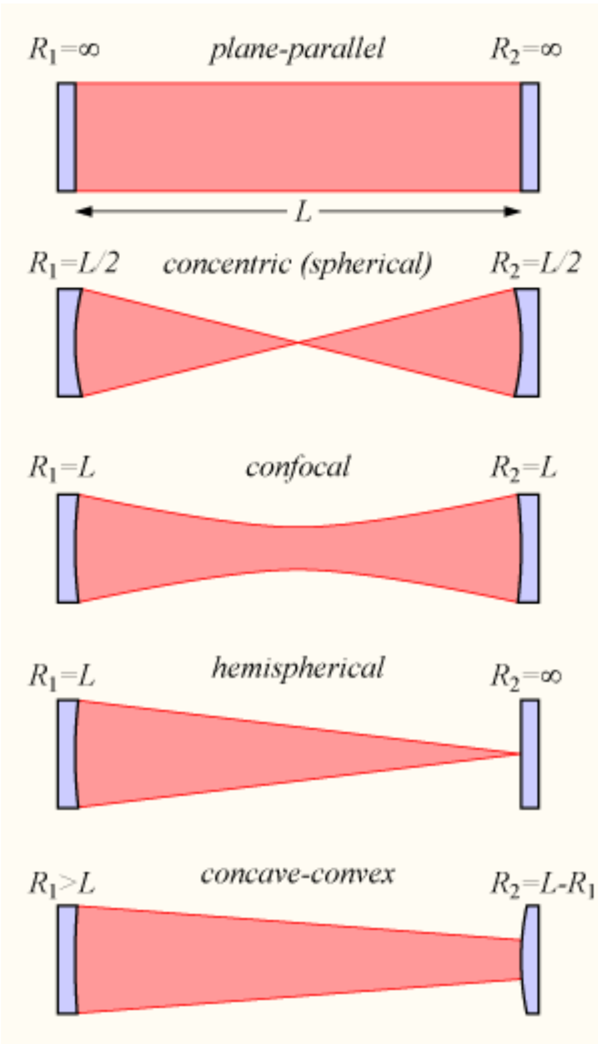


Laser cavity critical for an intense directed beam

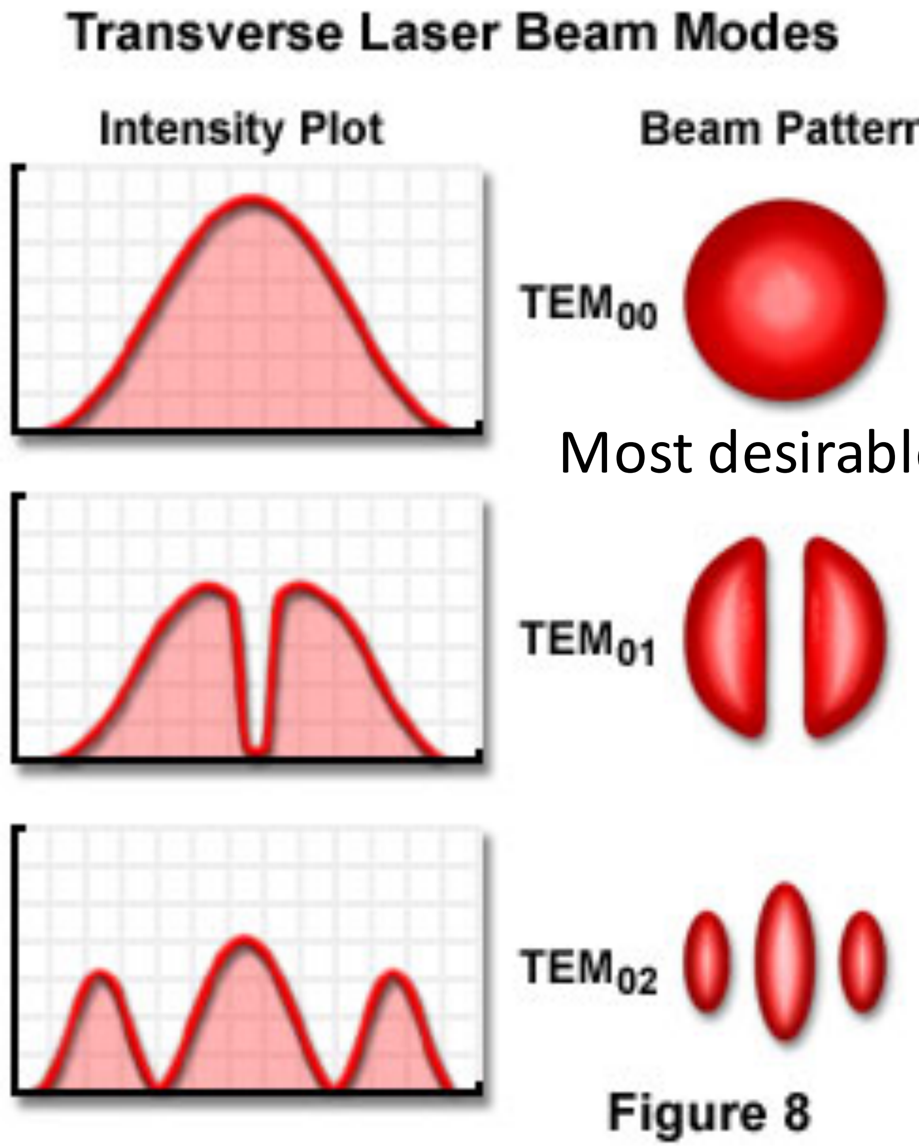


Cavity design and beam shape

Cavity designs



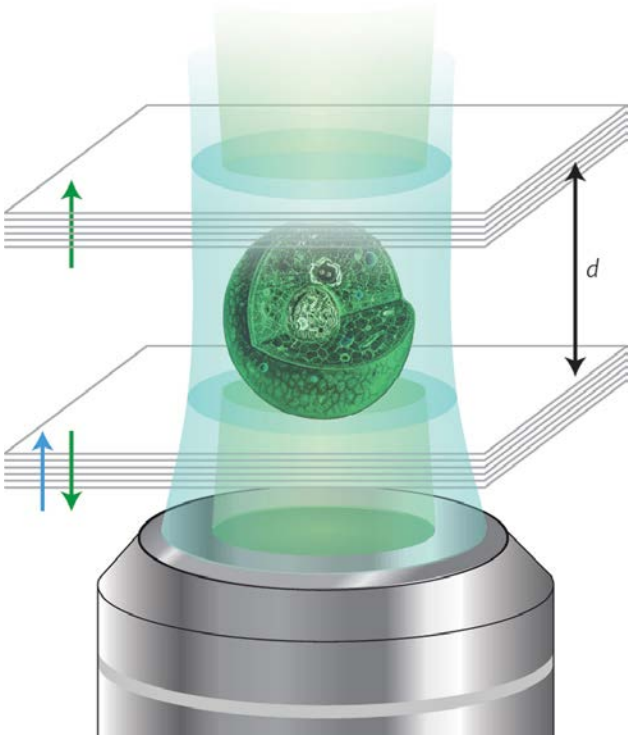
http://en.wikipedia.org/wiki/Optical_cavity

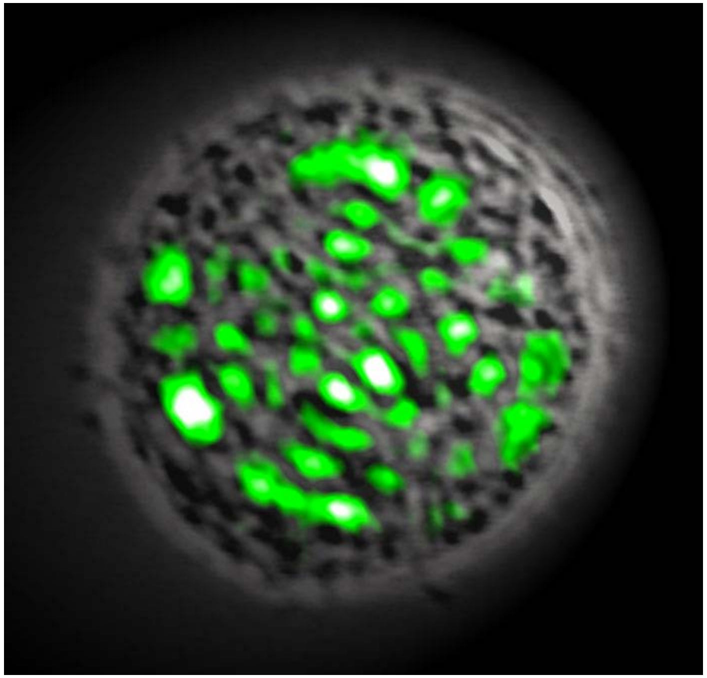


Most desirable

http://www.olympusmicro.com/primer/lightandcolor/lasersintro.html

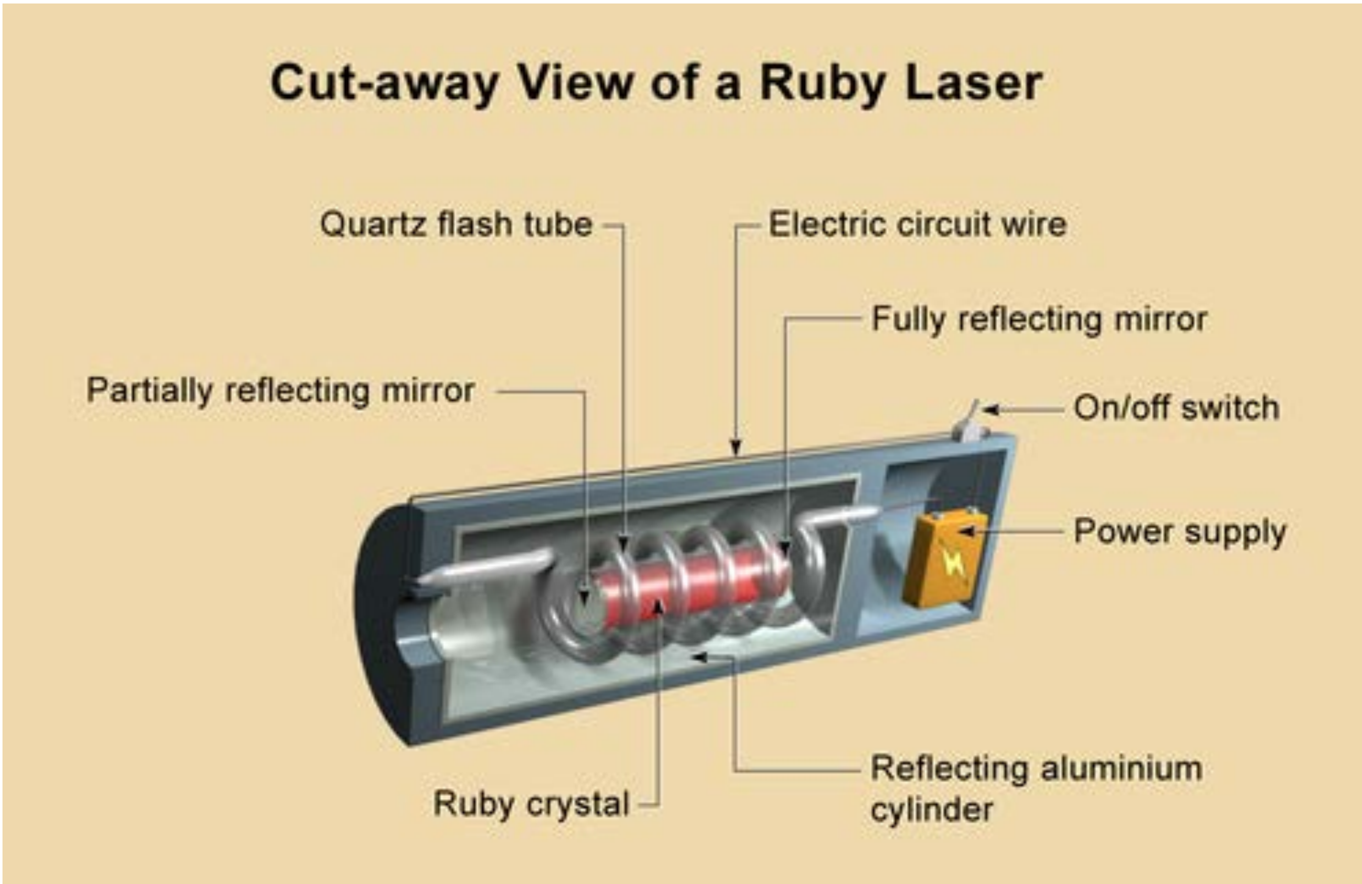
You can turn almost anything into a (bad) laser





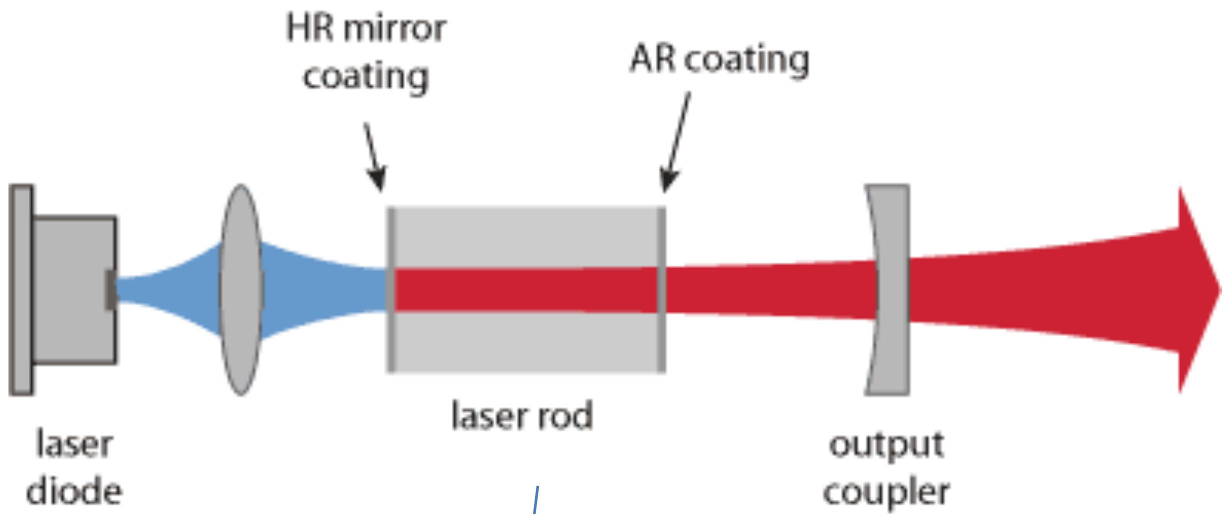
Gather and Yun (2011)

The first laser ever made…



http://en.wikibooks.org/wiki/Wikijunior:How_Things_Work/Laser

Diode pumped solid state (DPSS) lasers



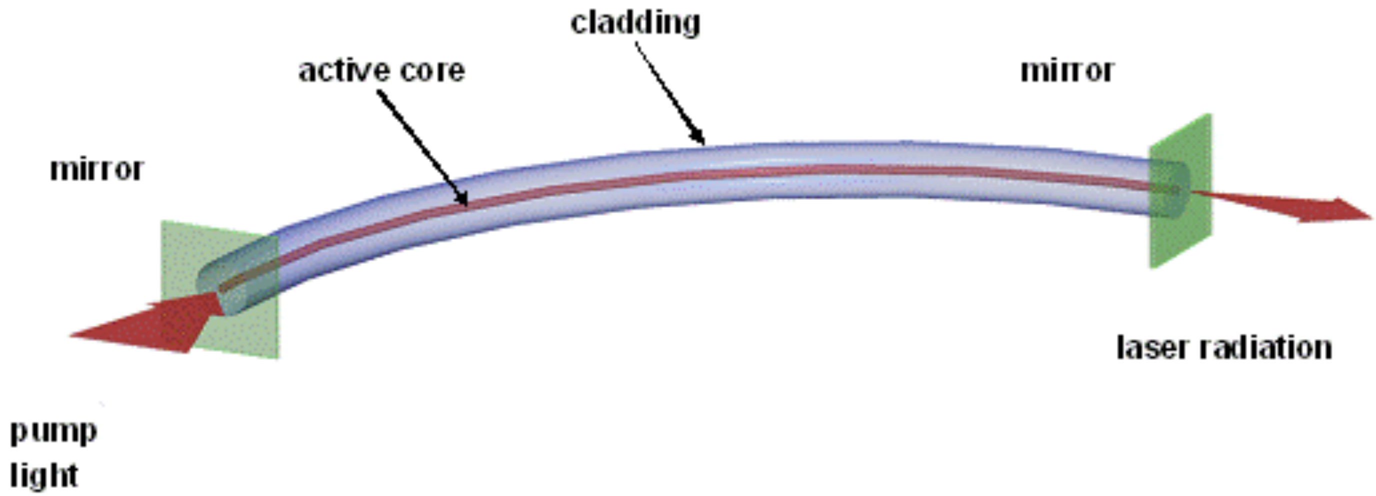
Laser diode

Sometimes a specially doped laser crystal that produces the desired spectral lines

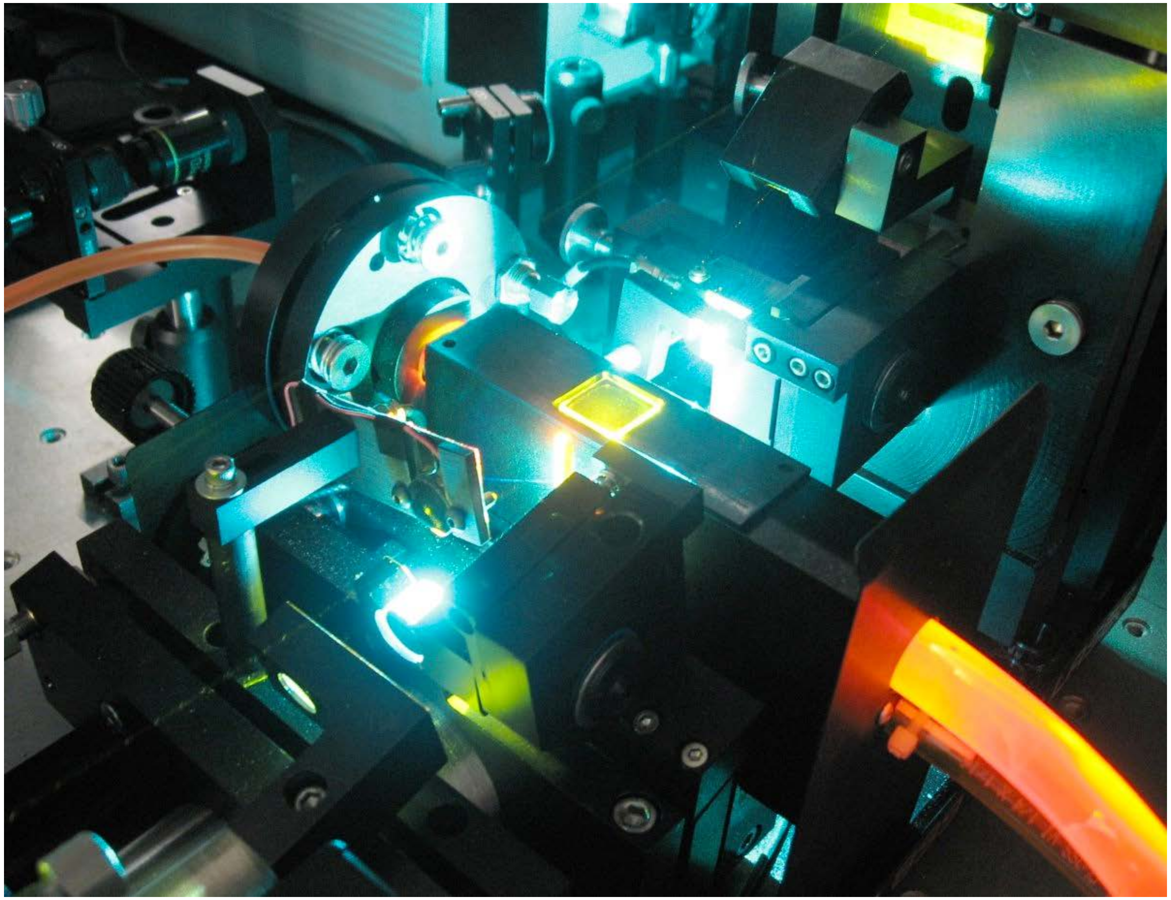
Nd:YAG
Laser rod

http://www.rp-photonics.com/solid_state_lasers.html

Fiber lasers

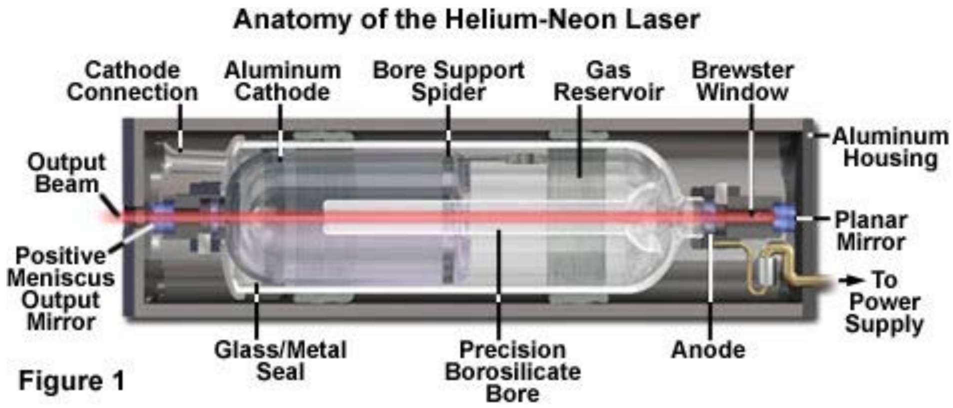


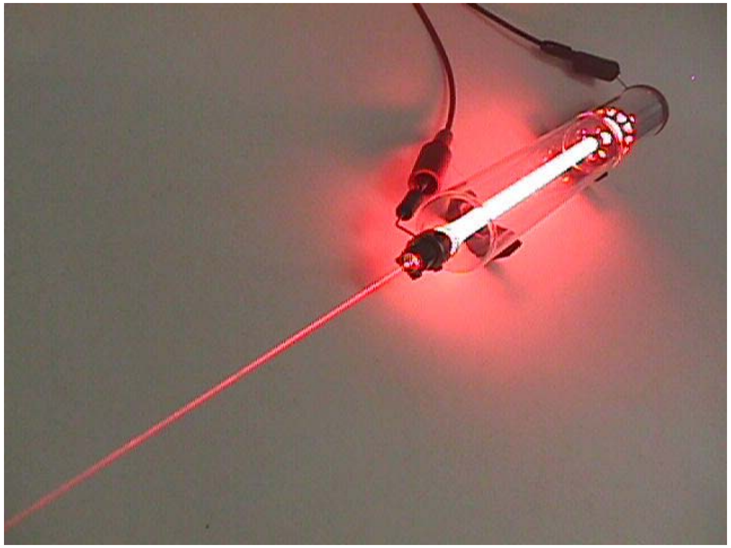
Dye laser



https://commons.wikimedia.org/wiki/File:Coherent_899_dye_laser.jpg

Helium-Neon (HeNe) laser





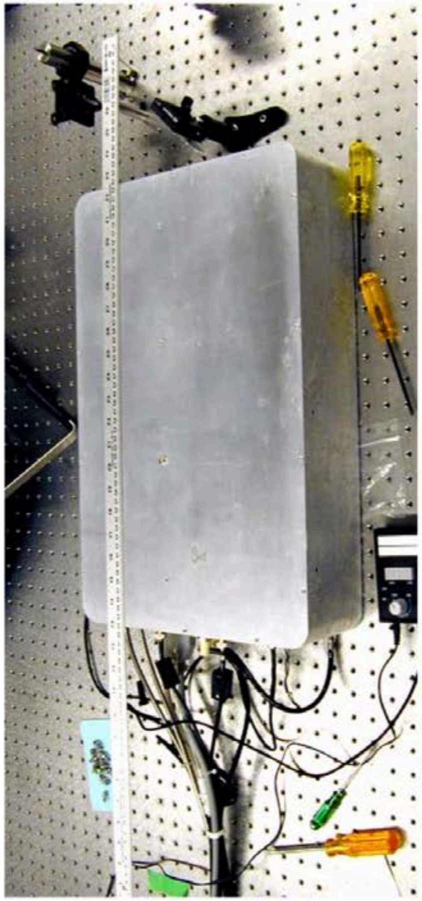
Titanium Sapphire (Ti:S) Laser

1991: Argon pump and Ti:S

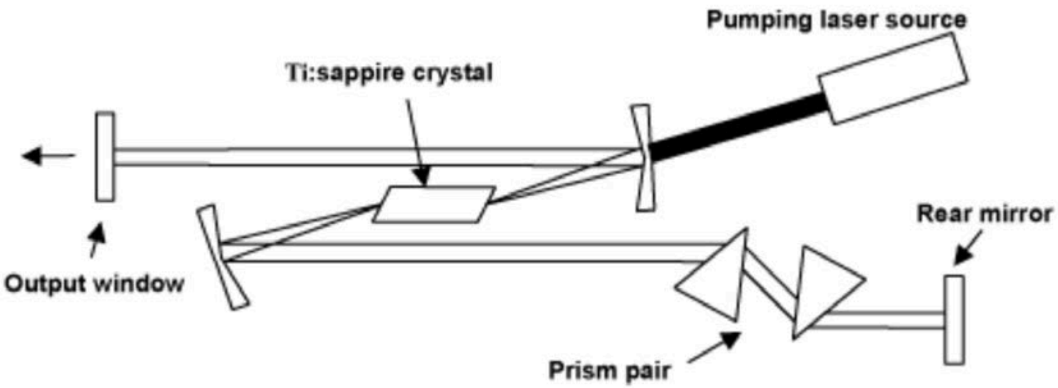
1997: Diode pumped Nd-vanadate 5 W pump

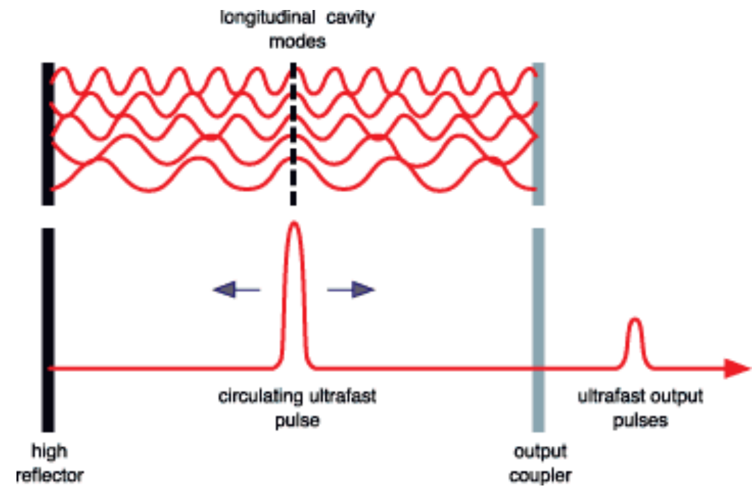
1998: Diode pumped Nd-vanadate 10 W pump

1999: Diode Pump and Ti:S resonator in a single case.



Titanium Sapphire (Ti:S) Laser

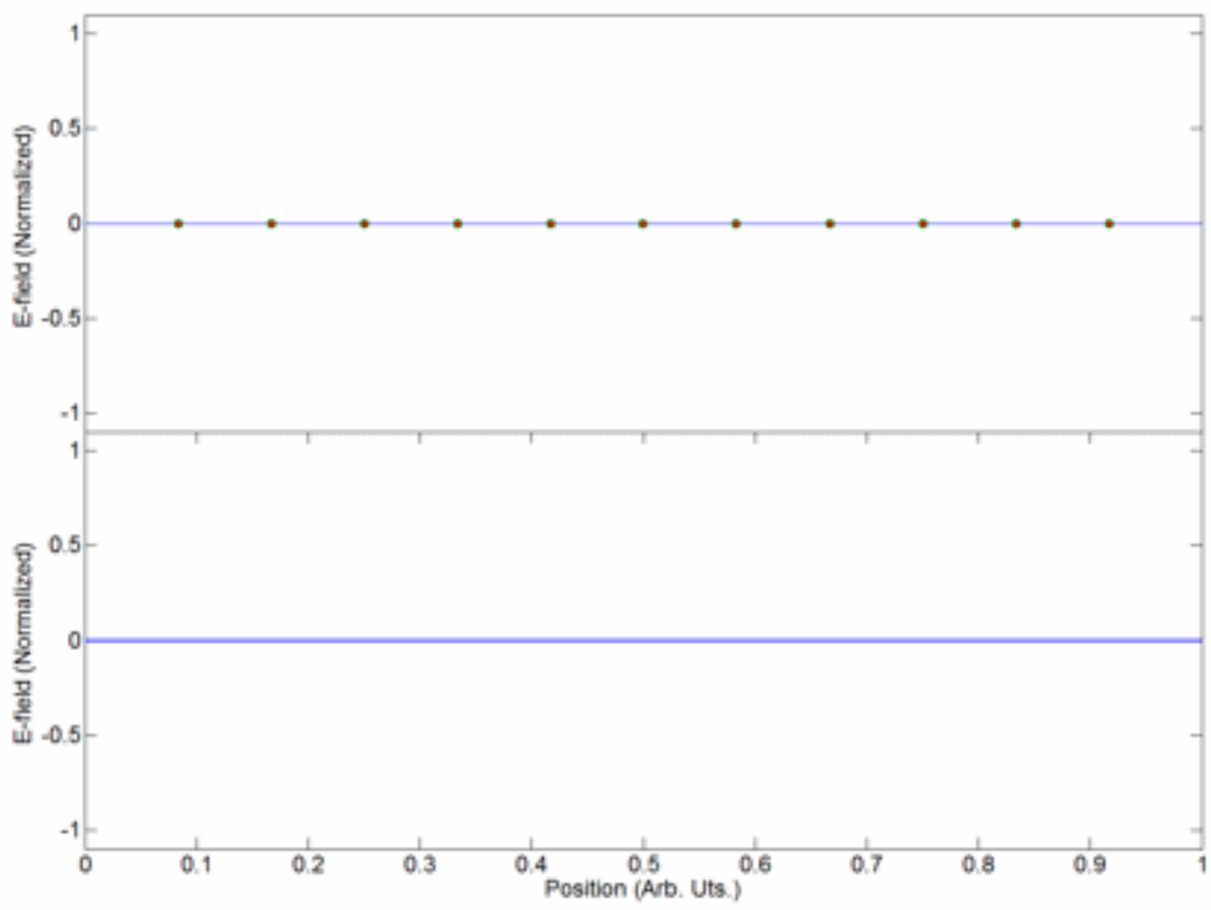




- Tunable wavelength in the red-near infrared (NIR) range
- Produces intense ultrashort pulses via mode-locking at MHz repetition rate (typically ~ 100 fs pulses at 80 MHz)

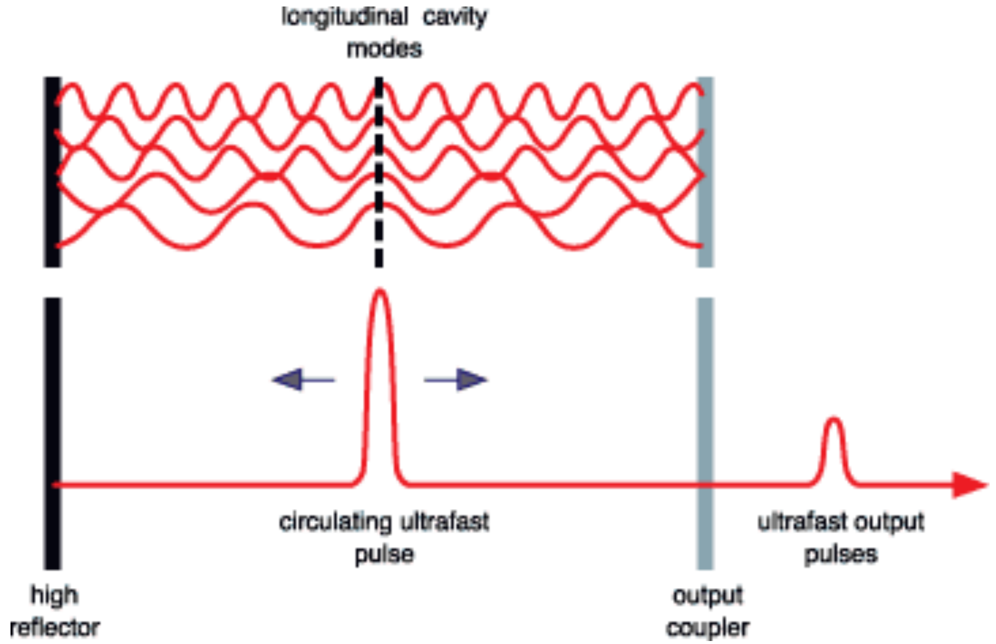
http://spie.org/Images/Graphics/Newsroom/Imported/may04/practicalfig1.gif

Mode-locked laser cavity



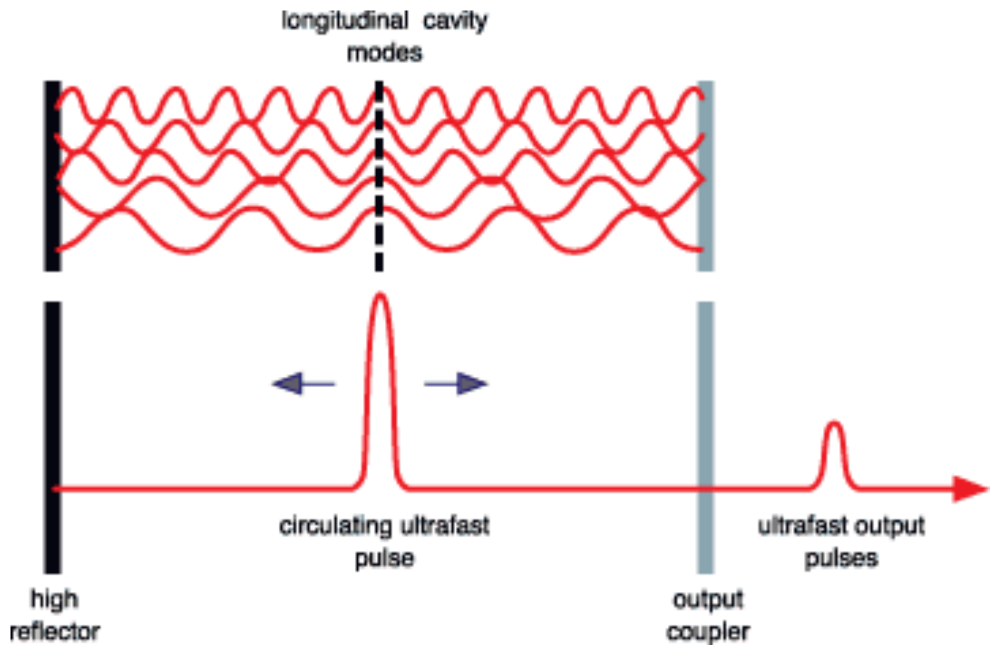
https://commons.wikimedia.org/wiki/File:Modelocking.gif

Titanium Sapphire (Ti:S) Laser



A Ti:S laser pulses at 80 MHz – how long is its cavity?

Titanium Sapphire (Ti:S) Laser



A Ti:S laser pulses at 80 MHz – how long is its cavity?
Round trip: $3 \cdot 10^8$ m/s / 80 MHz = 3.75 m
Cavity length: 3.75 m / 2 = 1.875 m

Time-bandwidth product

- Time and frequency are Fourier pairs
- Pulse duration (t) and optical bandwidth (Δf) are linked
- $t \cdot \Delta f \approx 0.4$ (for Gaussian pulse)

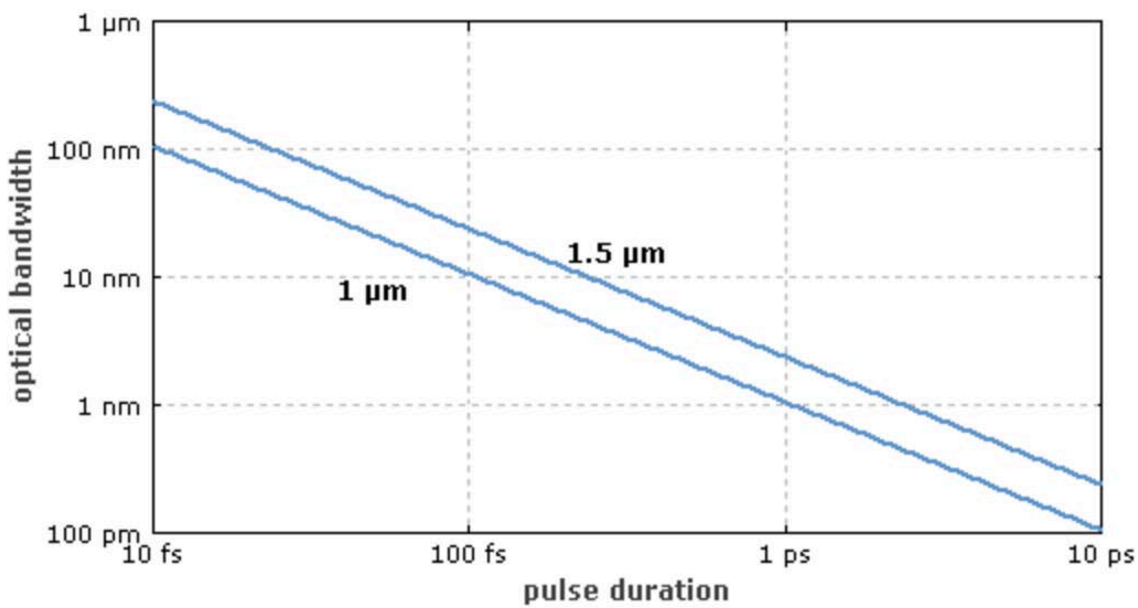
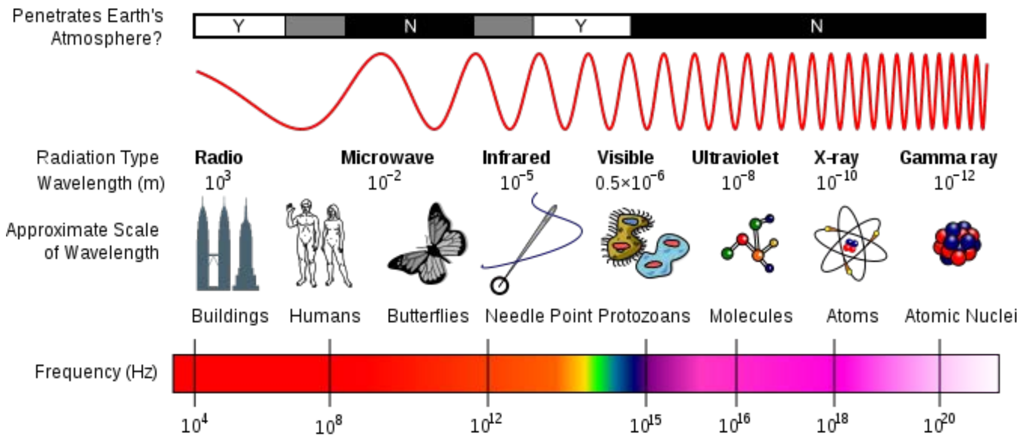
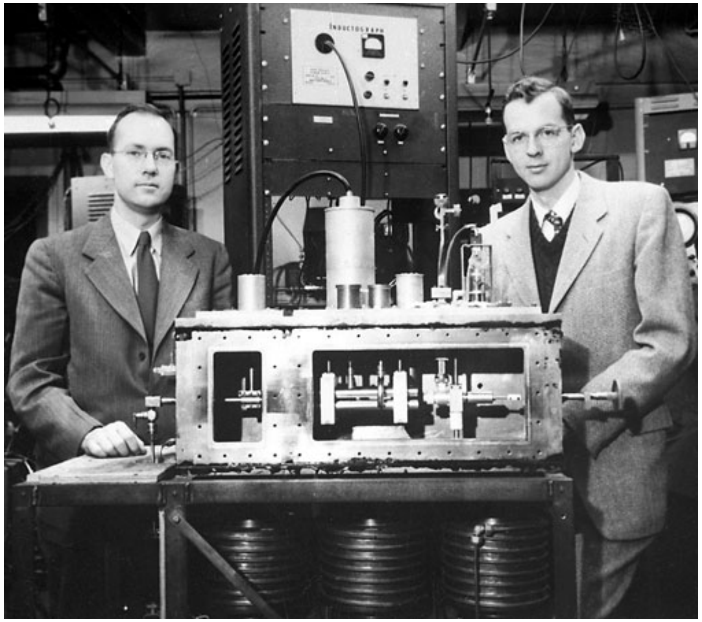


Figure 1: Optical bandwidth of sech^2-shaped bandwidth-limited pulses. Different curves apply for different center wavelengths due to the conversion from frequency to wavelength intervals.

Wavelength-range

- Principles of laser operation are applicable to the whole electromagnetic spectrum.
- 1st demonstration of stimulated emission was done in the microwave range (MASER)

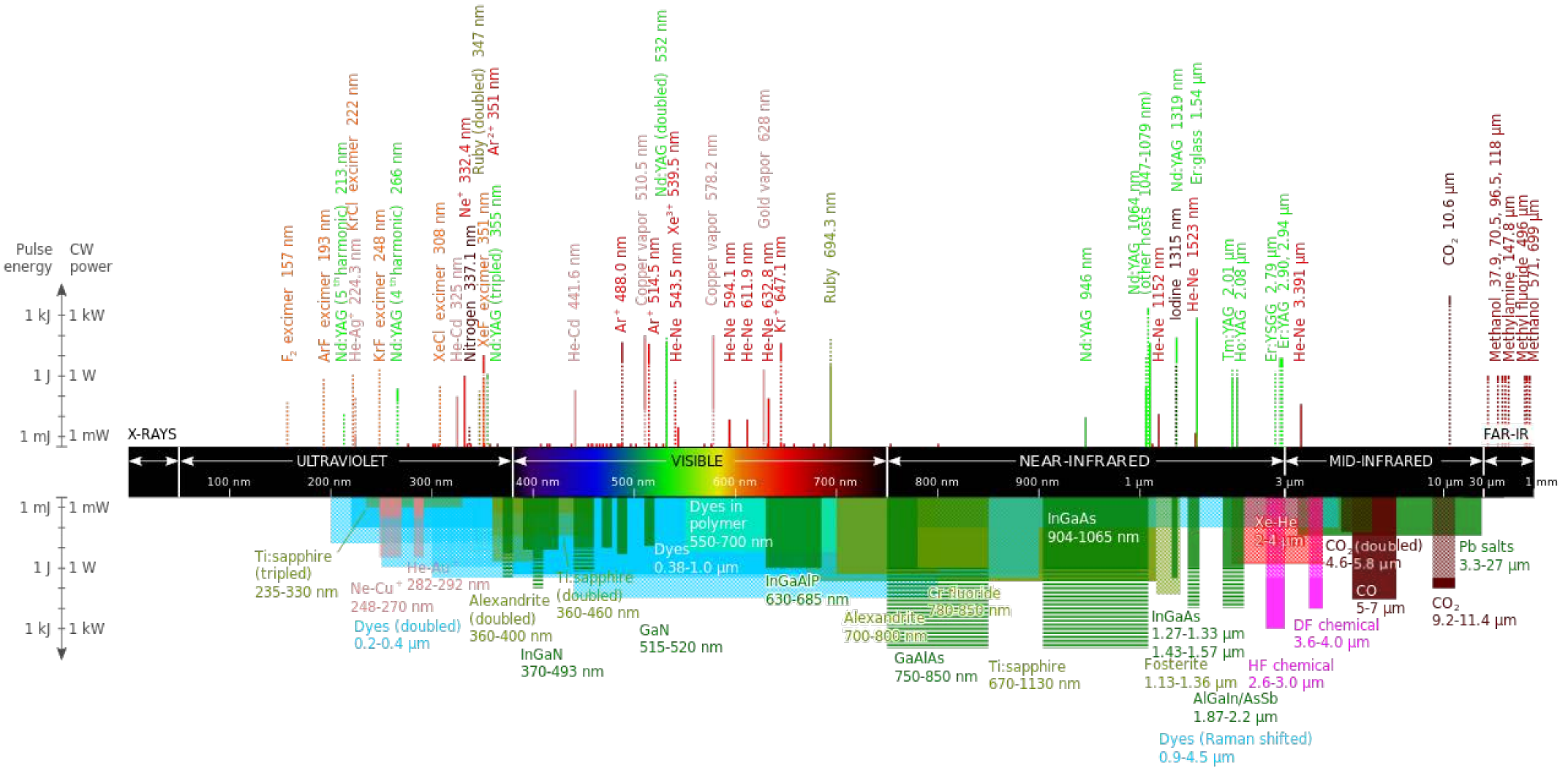




Townes (Nobel 1964) and Gordon

http://en.wikipedia.org/wiki/File:EM_Spectrum_Properties_edit.svg

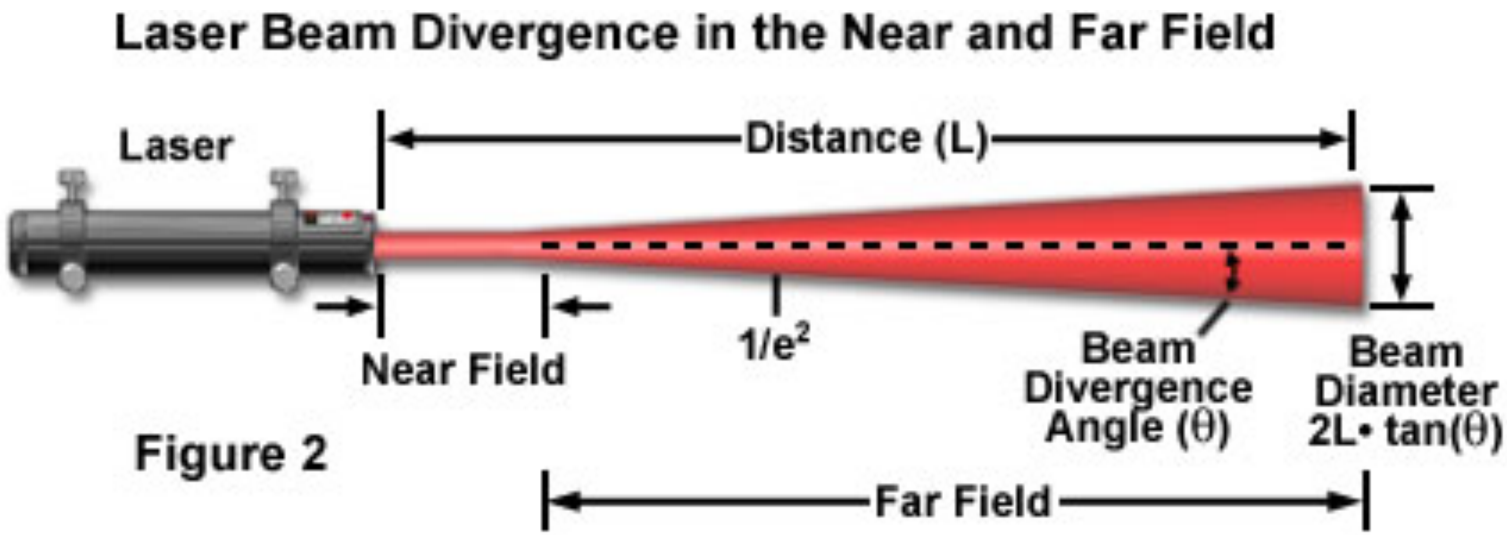
Wavelength-range



Ti:S 670 - 1130 nm

Nd:YAG (neodymium-doped yttrium aluminium garnet)

Laser propagation



Begins at A_0^2/λ,
where A_0
= beam diameter at exit of laser

The phase of the beam becomes ordered and predictable at the far field.
The divergence of a gaussian beam can be predicted by gaussian beam theory.

http://www.olympusmicro.com/primer/techniques/microscopylasers.html

Coherence

- **Coherence**: degree to which a wavefront can interfere with itself
  - Degrees: incoherent → partially coherent → coherent
- **Coherence length**: length over which a wave can interfere with itself, when shifted in time (width of temporal autocorrelation)
  - Directly related to pulse duration t ($L = c \cdot t$)
  - Inversely proportional to bandwidth ($L \approx \lambda^2/\Delta\lambda$)
  - Ti:S-laser example: 100 fs → $3 \cdot 10^8$ m/s · 100 fs = 30 µm

Coherence

Spatial coherence →

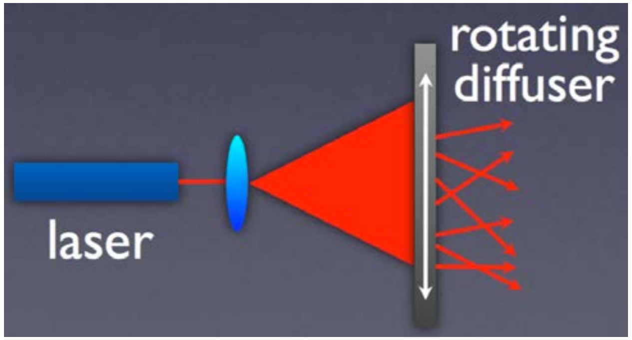
Temporal coherence ↓

?

Coherence

Spatial coherence →

Temporal coherence →



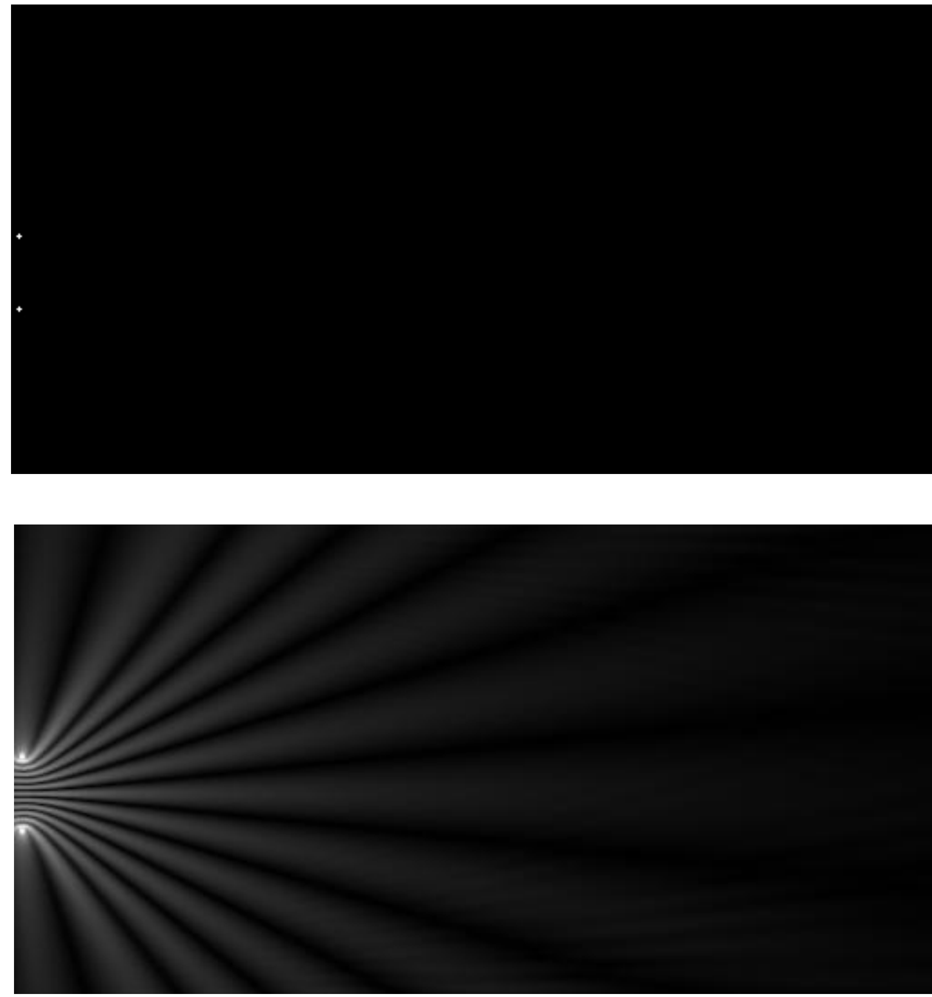
Throwing stones

One source

Two point-sources

Pure, identical frequency

Broad-band, correlated

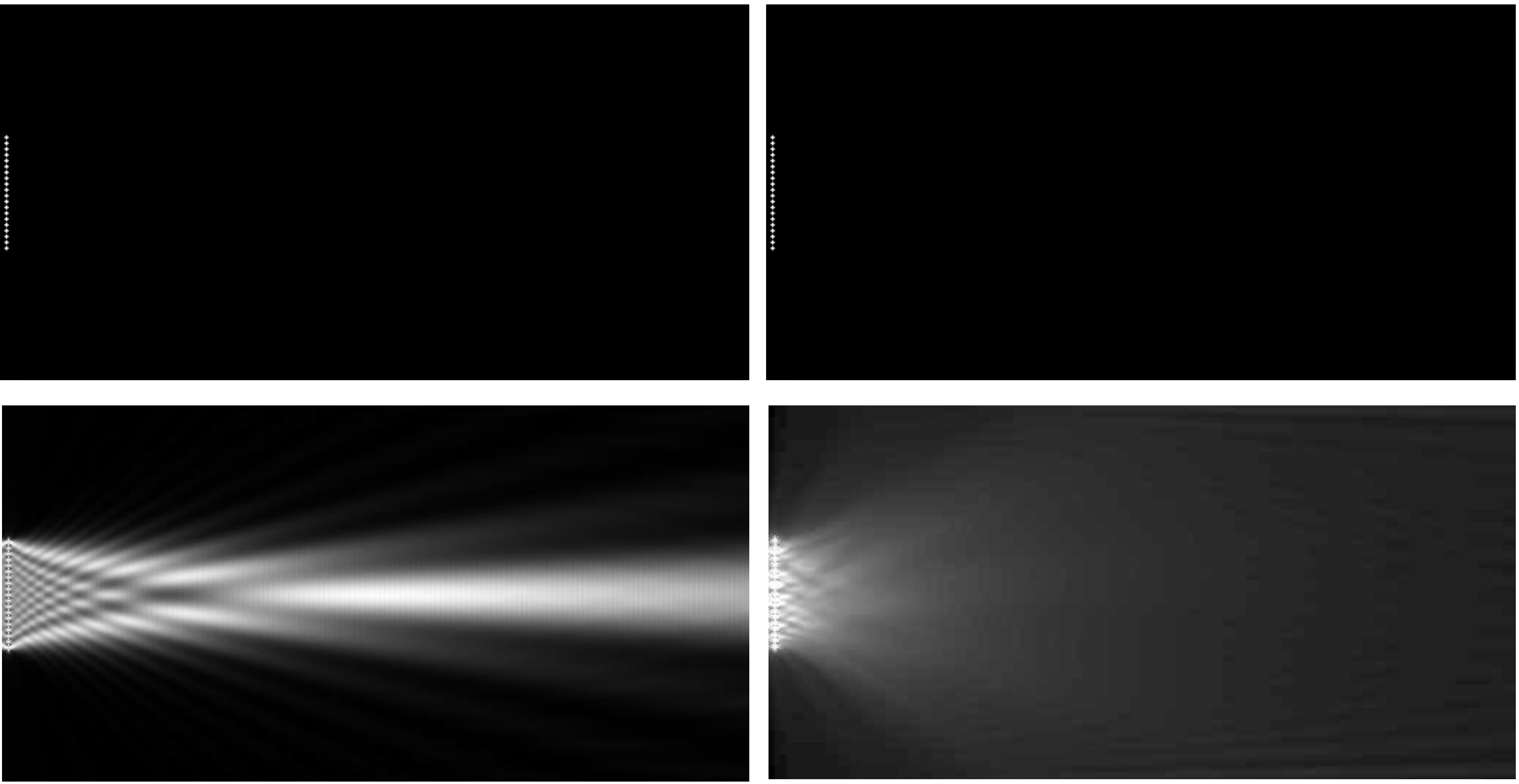


Two point-sources

Broad-band, uncorrelated

Extended sources

Two different light sources




White LED Strobe
Cool running, produces bright, clear, wave patterns
Sloped Foam Beach
Eliminates reflections
Ripple Generator
Producing interference pattern with two point sources
Ripple Tank
Base and Rod
(not included)
Detachable Legs
Viewing Screen
(included)
Point Sources
(3 sizes)
Refractors
Convex, Concave and Trapezoid
Curved Reflector
Plane Wave
and multiple source
Diffraction Barriers

Ripple tank