Combining laser light with synchrotron radiation

Properties of Laser Light

- coherence
  - interferometer
    - measuring distances
    - measuring wavelength
  - speckle measurements
    - structure reconstruction

Properties of Laser Light

- coherence
- intensity (brightness)
    - melting of surfaces
        - study of phase transitions (pump probe)
    - plasma production
        - properties of the plasma state
        - ion and cluster production (laser ablation)
        - electron production (electron gun for linac)
    - higher harmonic generation
        - strong field effect

Properties of Laser Light

- coherence
- intensity (brightness)
- spectral resolution (monochromatic)

high resolution absorption spectra

defined excitation of arbitrary lines

line width of continuous lasers <1MHz (4neV)

example Eu

hyper fine structure (quadrupole) 192 MHz (0.8μeV)

isotope shift 2.8 GHz (12μeV)

Properties of Laser Light

- coherence
- intensity (brightness)
- spectral resolution (monochromatic)
- spacial resolution (collimation)

high spacial coherence

→ point like source

→ optimal spot area possible $\sim\lambda^2$

Properties of Laser Light

- coherence
- intensity (brightness)
- spectral resolution (monochromatic)
- spacial resolution (collimation)
- temporal resolution

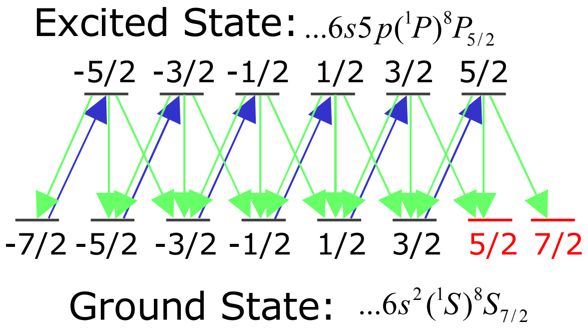
observing fast processes

ns:	atomic lifetimes	quality switched laser
ps:	melting processes	mode locked laser
fs:	chemical reactions	pulse compression
as:	photon absorption	high harmonic generation

Properties of Laser Light

- coherence
- intensity (brightness)
- spectral resolution (monochromaticity)
- spacial resolution (collimation)
- temporal resolution
- polarization

populate magnetically
aligned states


Excited State: $...6s5p(^1P)^8P_{5/2}$

Ground State: $...6s^2(^1S)^8S_{7/2}$

magneto optical trap (MOT)

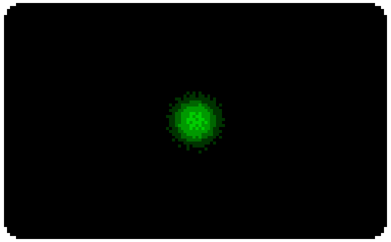
Properties of Laser Light

- coherence
- intensity (brightness)
- spectral resolution (monochromaticity)
- spacial resolution (collimation)
- temporal resolution
- polarization

How to Produce Laser Light

Laser Principle

Light **A**mplification by
Stimulated **E**mission of **R**adiation



Stimulated emission amplifies the existing light wave

What is light really?

A stream of particles?

A wave?

Something else?

Maxwell's equations

Gauß' Law

$$\nabla \cdot \vec{D} = \rho$$

No magnetic monopoles

$$\nabla \cdot \vec{B} = 0$$

Faraday's law

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

Ampère's Law

$$\nabla \times \vec{H} = \vec{J} + \frac{\delta \vec{D}}{\delta t}$$

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P}$$

$$\vec{B} = \mu_0 \left(\vec{H} + \vec{M} \right)$$

Wave equations

$$\nabla^2 \vec{E} = \epsilon \mu \frac{\delta^2 \vec{E}}{\delta t^2} \qquad \nabla^2 \vec{H} = \epsilon \mu \frac{\delta^2 \vec{H}}{\delta t^2}$$

Free Wave:

$$\vec{E} = \sum_i \vec{A}_i e^{i(\omega_i t + \vec{k}_i \cdot \vec{r})} + c.c.$$

Speed of light:

$$v = \frac{\omega_i}{k_i} = \frac{1}{\sqrt{\epsilon \mu}}$$

Transversal:

$$\vec{E} \cdot \vec{k} = 0$$

What is light really?

A stream of particles?

A wave?

Something else?

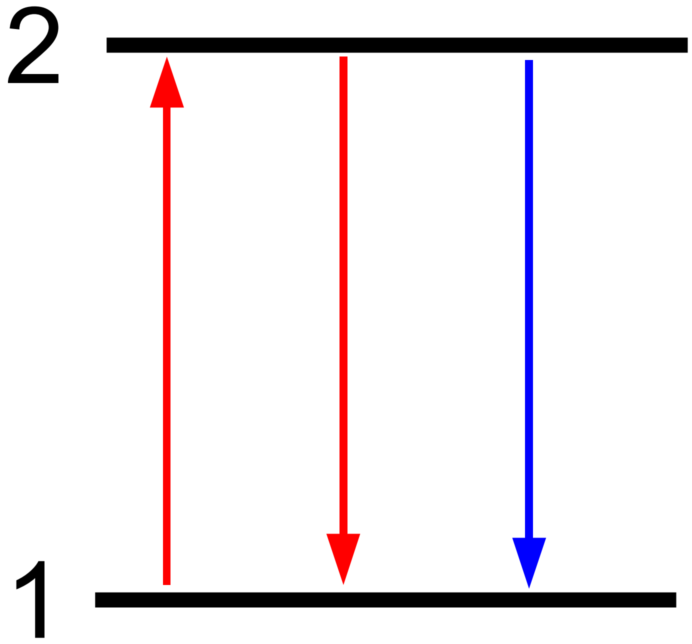
Semiclassical approximation

In most cases, the interaction of light with matter can be modeled by treating the **light as a classical wave** and the **atoms quantummechanically**

Light: The number of photons per mode is usually high

Matter: At room temperature most atoms are in the lowest states

Transition probabilities

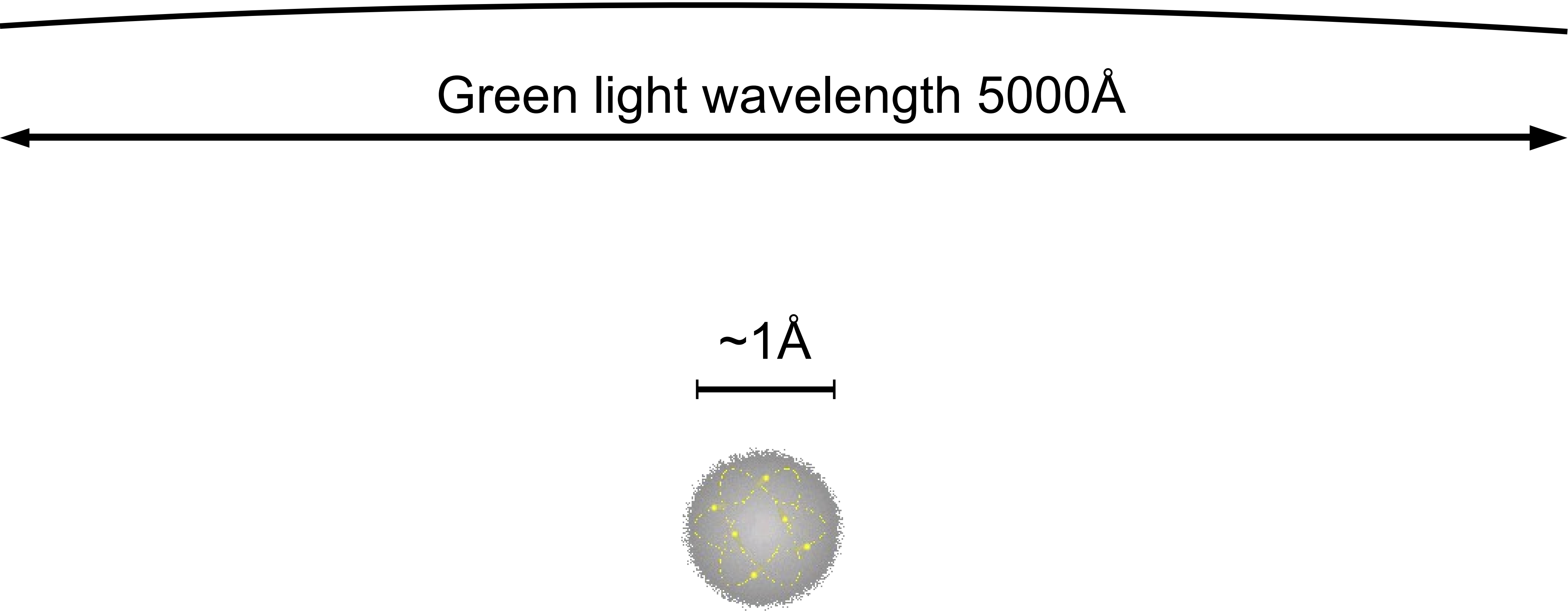


Absorption W_{12}

Stimulated emission W_{21}

Spontaneous emission A

Calculating the transitions



Green light wavelength 5000Å

~1Å

Approximations

- Wavelength much greater than atom
  (Dipole approximation)
- Interaction over many periods
  (time average)
- Weak perturbation
  (first order perturbation theory)

Atomic wave functions

Two energy eigenstates of an atomic system:

$$\Psi_1(\vec{r},t)=u_1(\vec{r})\exp\left[-i(E_1/\hbar)t\right]$$

$$\Psi_2(\vec{r},t)=u_2(\vec{r})\exp\left[-i(E_2/\hbar)t\right]$$

Superposition of eigenstates is a solution of the time dependent Schrödinger-equation:

$$\Psi=a_1\,\Psi_1+a_2\,\Psi_2$$

with $|a_1|^2+|a_2|^2=1$

Perturbation theory

Time independent atomic Hamiltonian: H_0

Time dependent perturbation:

$$H'(t) = \vec{\mu} \cdot \vec{E} = e\vec{r} \cdot \vec{E}_0 \sin \omega t$$

Ansatz:

$$\Psi = a_1(t)\Psi_1 + a_2(t)\Psi_2$$

Gives in first order:

$$\frac{d}{dt} a_2 = (1/i\hbar) H_{12} \exp(i\omega_0 t)$$

with: $H_{12}(t) = \int u_1^* H' u_2$ and $\omega_0 = (E_2 - E_1)/\hbar$

Absorption probability

Integration over a long time gives the **transition probability:**

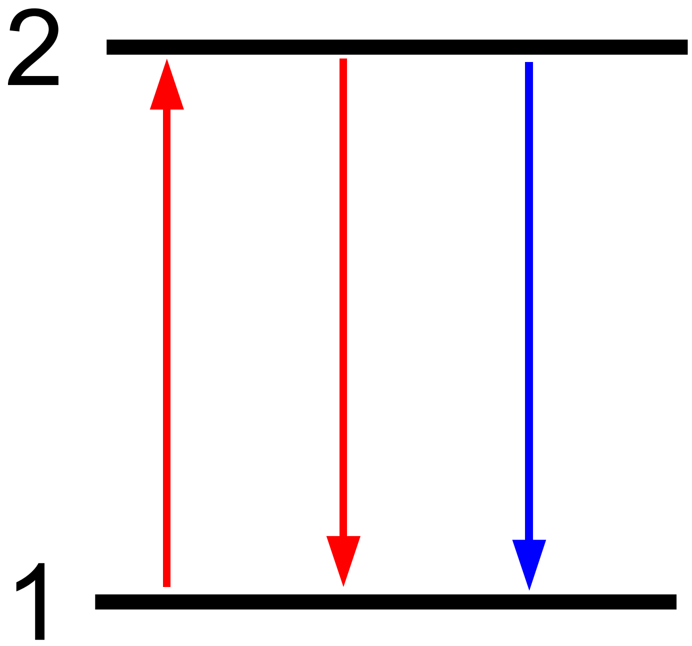
$$W_{12} = \frac{\left|a_2(t)\right|^2}{t} = \frac{\pi^2}{3\mathrm{h}^2} E_0^2 \left|\mu_{21}\right|^2 \delta(\omega - \omega_0)$$

with:

$$\vec{\mu}_{12} = \int u_2^* e \vec{r} u_1 \, dV$$

W_{12} depends on light intensity and atomic properties

Einstein Parameters



Absorption $W_{12}=B_{12}\rho(\omega)$

Stimulated emission $W_{21}=B_{21}\rho(\omega)$

Spontaneous emission A_{21}

$\rho(\omega)$: Spectral energy density

Spontaneous Emission A_{21}

Spontaneous emission cannot be calculated in the semiclassical approximation.

→QED

Einstein's argumentation

Thermal equilibrium:

$$A_{21} N_2 + B_{21} \rho(\nu) N_2 = B_{12} N_1 \rho(\nu)$$

Boltzmann distribution:

$$N_i = (g_i N / Z) e^{-E/kT}$$

Blackbody radiation:

$$\rho(\nu) = \frac{8\pi\nu^2}{c^3} \frac{h\nu}{e^{h\nu/kT} - 1}$$

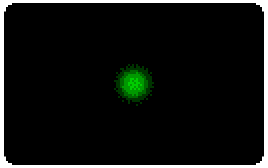
Einstein parameters

$$B_{12} = \frac{g_{12}}{g_{21}} B_{21}$$

$$A_{21} = \frac{8 \pi h \nu^3}{c^3} B_{21}$$

Laser Principle

Light **A**mplification by
Stimulated **E**mission of **R**adiation

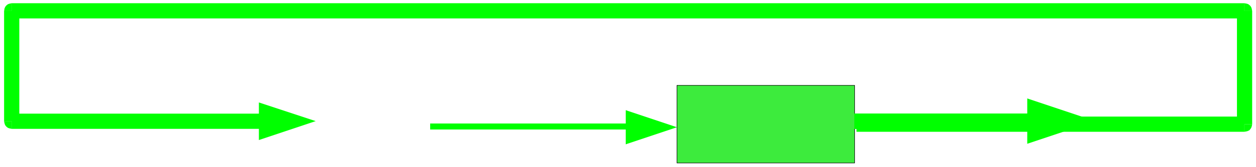


- Stimulated emission amplifies the existing light wave
- often within an optical resonator
- active medium excited by:
    - flash lamp
    - discharge
    - laser

Resonator

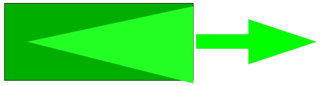
Laser with optical resonator:

- feedback turns an Amplifier into an Oscillator

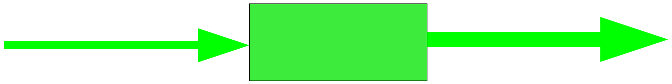


Laser without optical resonator:

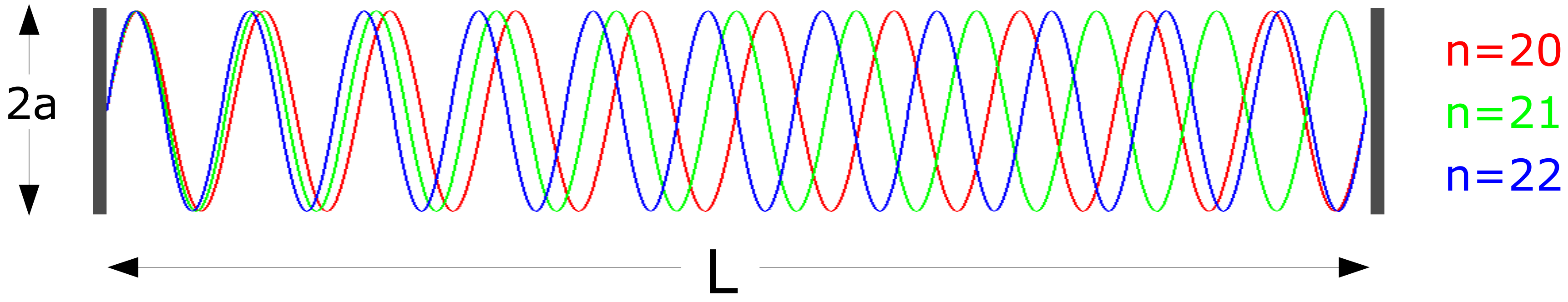
- amplified spontaneous emission (S)ASE
  - amplification of a random mode



- amplification of a seeding beam

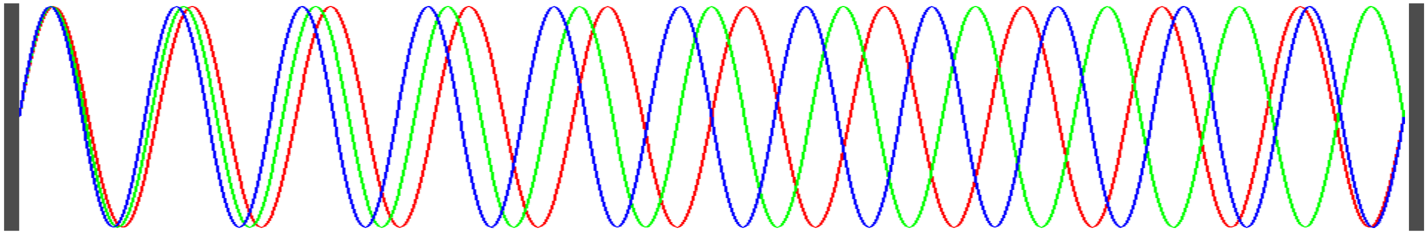


Fabry-Perot Resonator



- standing waves between flat mirrors
- integer of half a wavelength must fit into the resonator $\lambda = \frac{2L}{n}$
- L=50cm, λ=500nm: n=20 000
- hard to align long resonators $F = \frac{a^2}{\lambda L}$
- high diffraction losses for small Fresnel-number

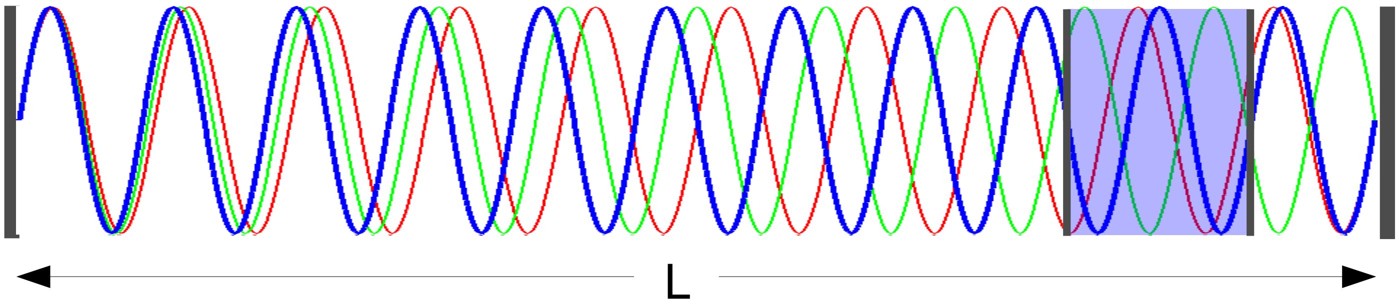
Using the Modes



What do we need?

- spectral resolution
- coherence
  - → Select a single mode
- high intensity
- short pulses
  - → Couple the modes to a short pulse

Mode Selection



mode separation (free spectral range):

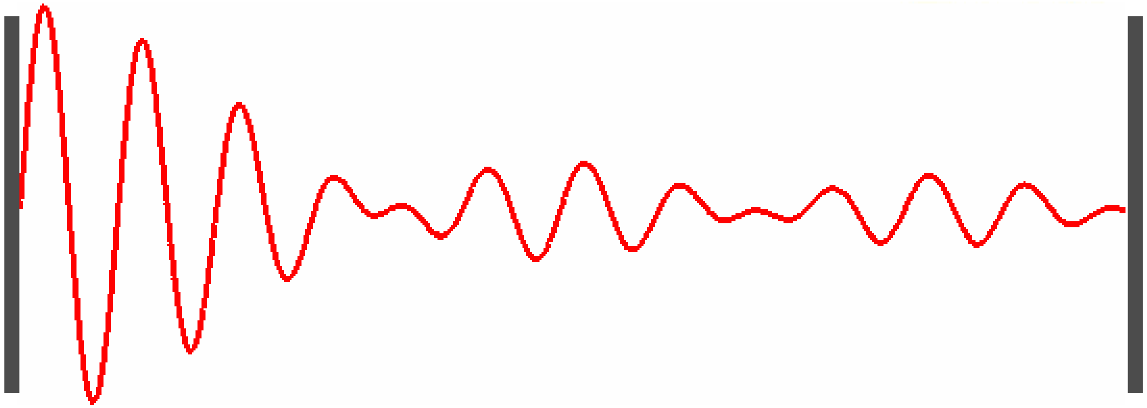
- $\Delta\nu = \frac{c}{2L}$
- 300 Mhz for ½ m cavity
- 100 GHz for the thin etalon in the Ti:Sa

~1nm at λ=600nm

Mode Coupling

producing pulse trains by fixing the phases of the modes

coupling 6 waves n=20-25



coupling 101 waves n=20000-20100