

# Combining laser light with synchrotron radiation

## Part 2

<http://www.joachimschulz.de/laser/>

# Literature

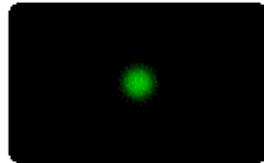
Orazio Svelto, “Principles of Lasers”,  
Plenum Press, New York (1989)

Wolfgang Demtröder, “Laser spectroscopy”,  
Springer, Berlin (2005)

Max Born and Emil Wolf, “Principles of optics”,  
Cambridge University Press (1999)

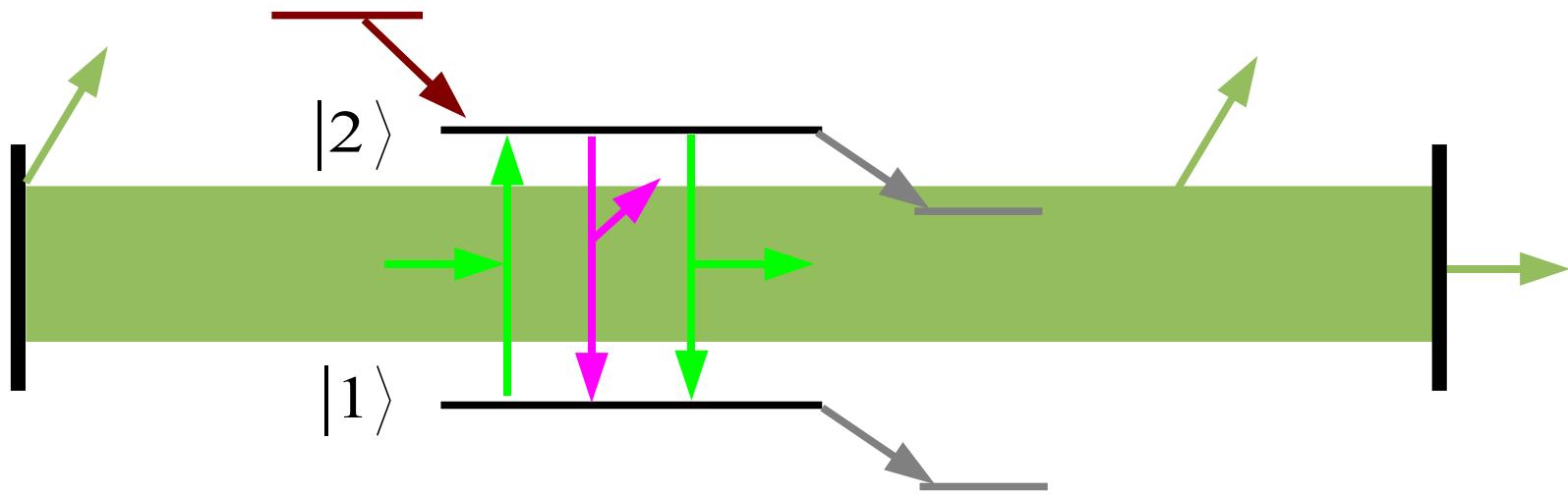
# Laser Principle

**Light Amplification by  
Stimulated Emission of Radiation**



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

# Rate Equation



$$\frac{dN_2}{dt} = \begin{matrix} \text{pump} \\ P \end{matrix} - N_2 A_{21} - N_1 B_{12} \rho + N_2 B_{21} \rho - N_2 R_2$$

spont.  
Emiss.

Absorption      stim. Emission      Relaxation

$$\frac{dN_1}{dt} = +N_2 A_{21} - N_1 B_{12} \rho + N_2 B_{21} \rho - N_1 R_1$$

$$\frac{d\rho}{dt} = -N_1 B_{12} \rho + N_2 B_{21} \rho - \frac{\beta \rho}{h\nu}$$

# Rate Equations

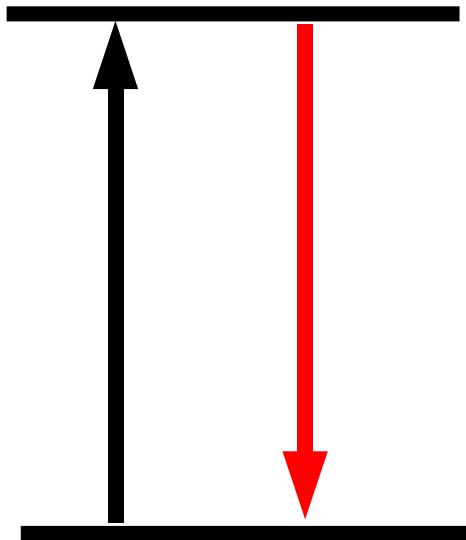
$$\frac{dN_2}{dt} = P - N_2 A - (N_2 - N_1) B \rho - N_2 R_2$$

$$\frac{dN_1}{dt} = N_2 A + (N_2 - N_1) B \rho - N_1 R_1$$

$$\frac{d\rho}{dt} = (N_2 - N_1) B \rho - \frac{\beta \rho}{h \nu}$$

Lasing occurs only if  $N_2 > N_1$ : Inversion

# Two level system



$$\frac{dN_2}{dt} = -N_2 A - (N_2 - N_1) B \rho$$

$$\rightarrow \frac{N_2}{N_1} = \frac{B \rho}{A + B \rho}$$

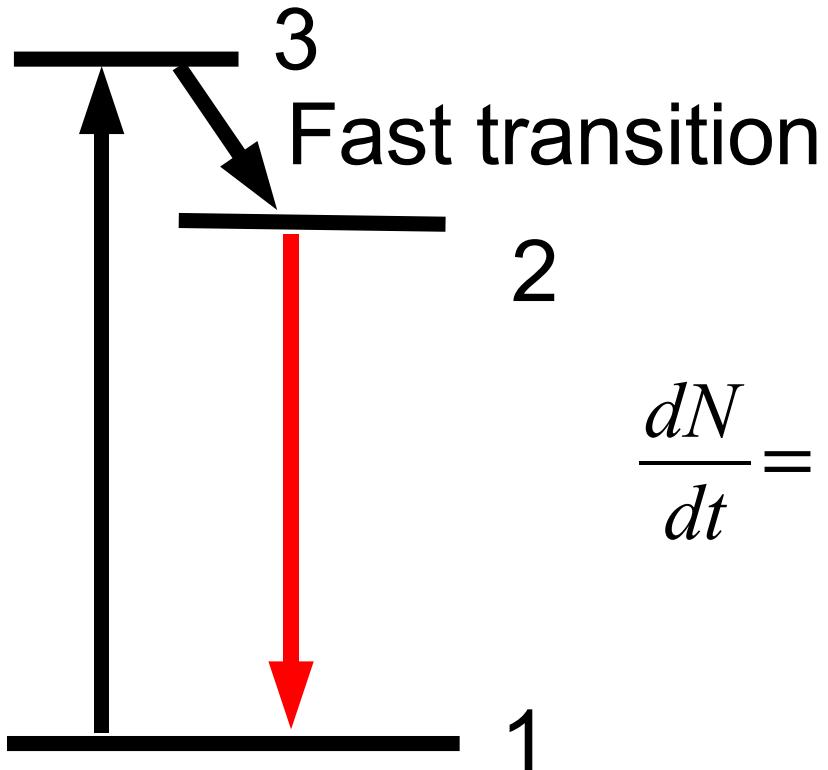
No inversion!  
No lasing!

$$\frac{dN_2}{dt} = P - N_2 A - (N_2 - N_1) B \rho - N_2 R_2$$

$$\frac{dN_1}{dt} = N_2 A + (N_2 - N_1) B \rho - N_1 R_1$$

$$\frac{d\rho}{dt} = (N_2 - N_1) B \rho - \frac{\beta \rho}{h\nu}$$

# Three level system



$$N_t = N_2 + N_1$$

$$N = N_2 - N_1$$

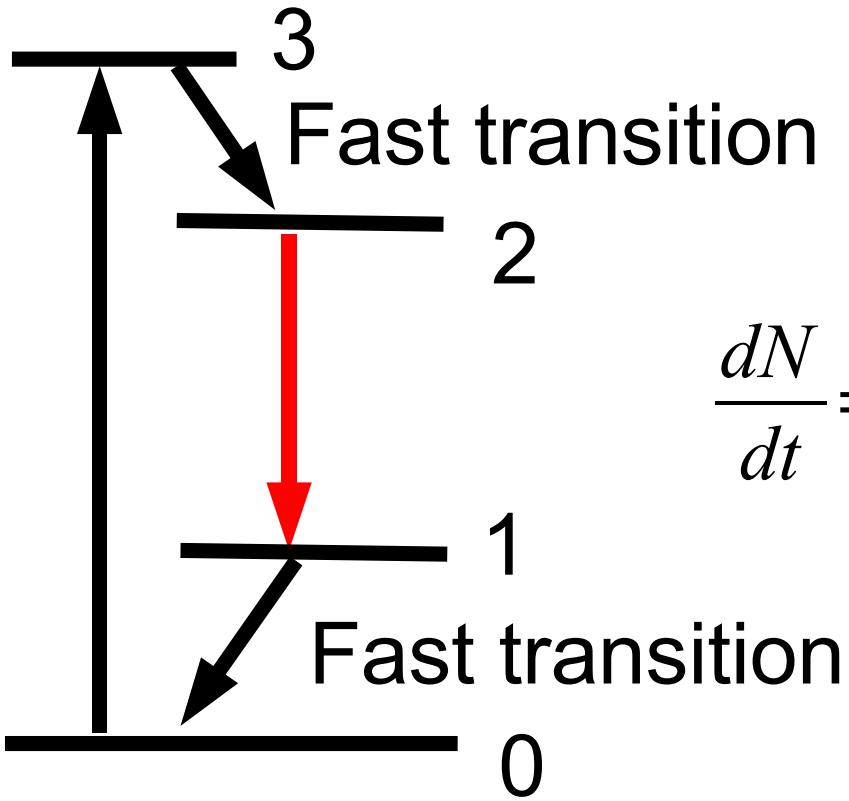
$$\frac{dN}{dt} = W_p(N_t - N) - 2B\rho N - (N_t + N)A$$

$$\frac{dN_2}{dt} = P - N_2 A - (N_2 - N_1)B\rho - N_2 R_2$$

$$\frac{dN_1}{dt} = N_2 A + (N_2 - N_1)B\rho - N_1 R_1$$

$$\frac{d\rho}{dt} = (N_2 - N_1)B\rho - \frac{\beta\rho}{h\nu}$$

# Four level system



$$N_l = 0$$

$$\frac{dN}{dt} = W_p(N_t - N) - B\rho N - NA$$

$$\frac{dN_2}{dt} = P - N_2 A - (N_2 - N_1)B\rho - N_2 R_2$$

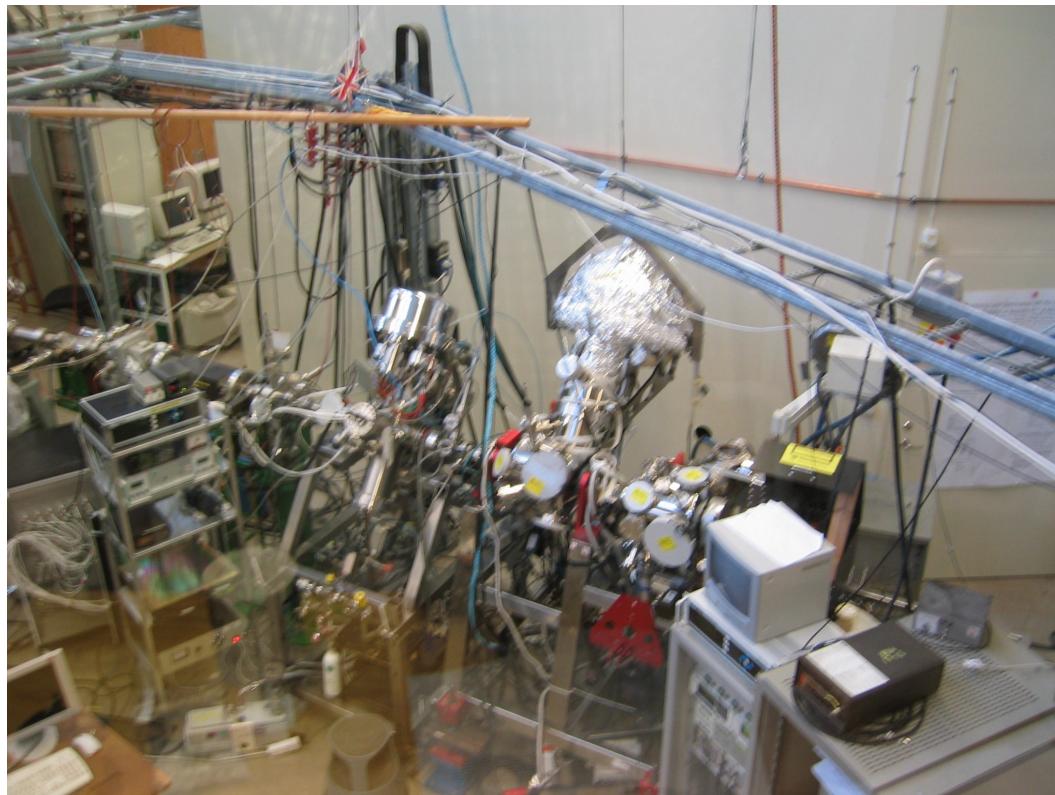
$$\frac{dN_1}{dt} = N_2 A + (N_2 - N_1)B\rho - N_1 R_1$$

$$\frac{d\rho}{dt} = (N_2 - N_1)B\rho - \frac{\beta\rho}{h\nu}$$

# Laser System at MAX II - I411

MAX II time structure

- 100 Mhz repetition rate: 10ns distance



# Laser System at MAX II • I411

desired properties:

- wide tuning range
  - for absorption spectroscopy
  - for reaching different targets
- continuous wave
  - no timing necessary
  - very high resolution

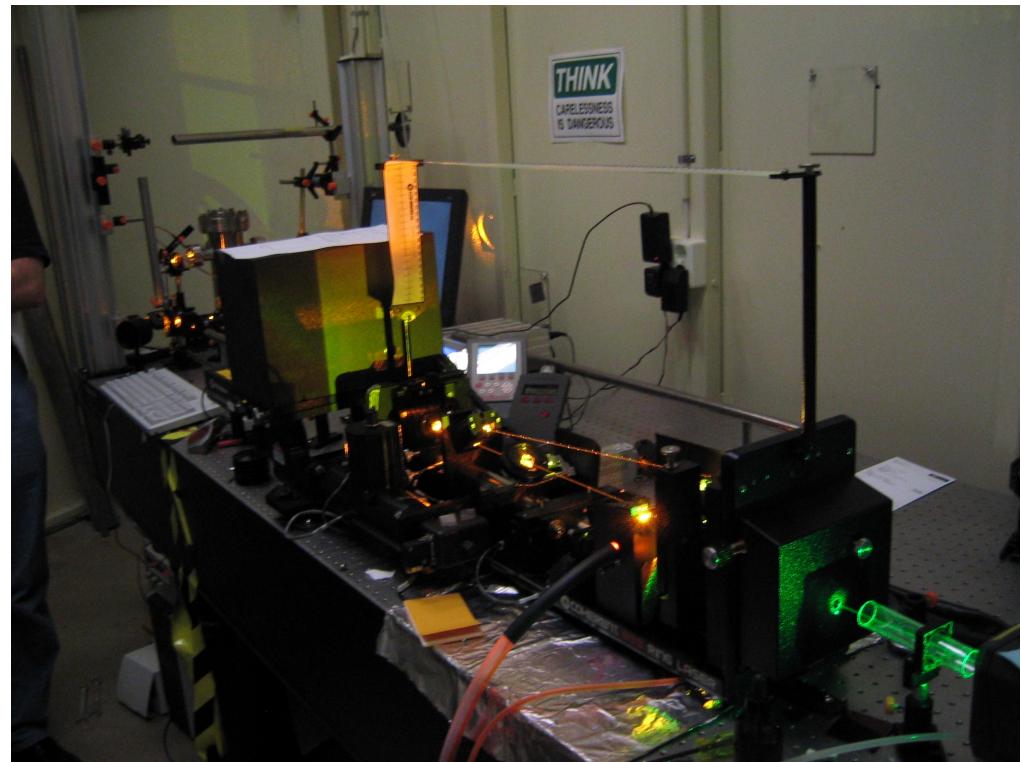
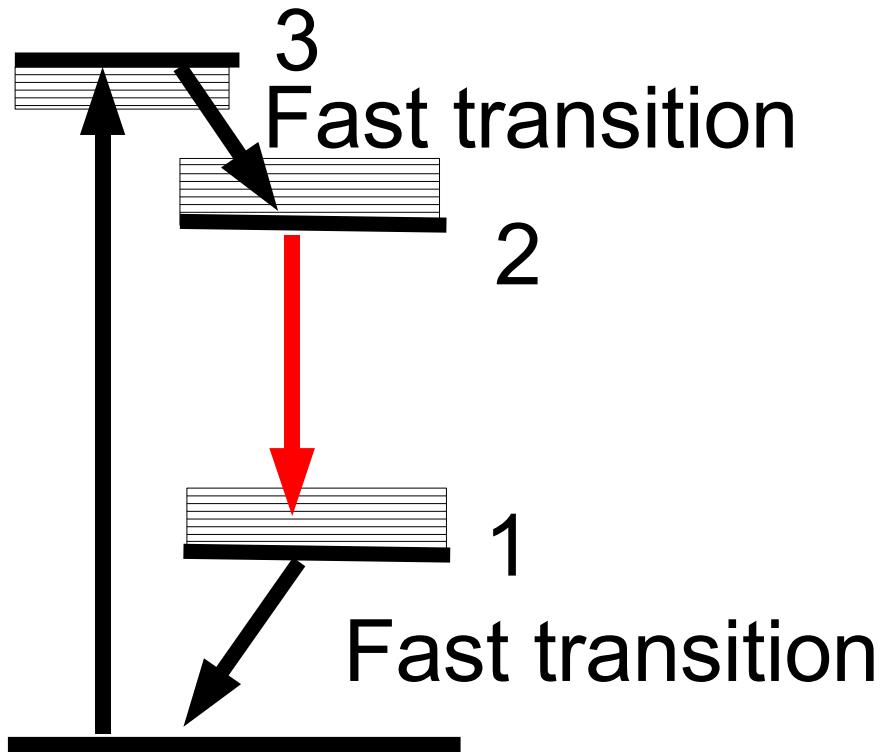
chosen system:

- Titanium dotted Saphire: 770-1000nm
- laser dyes: 550- nm

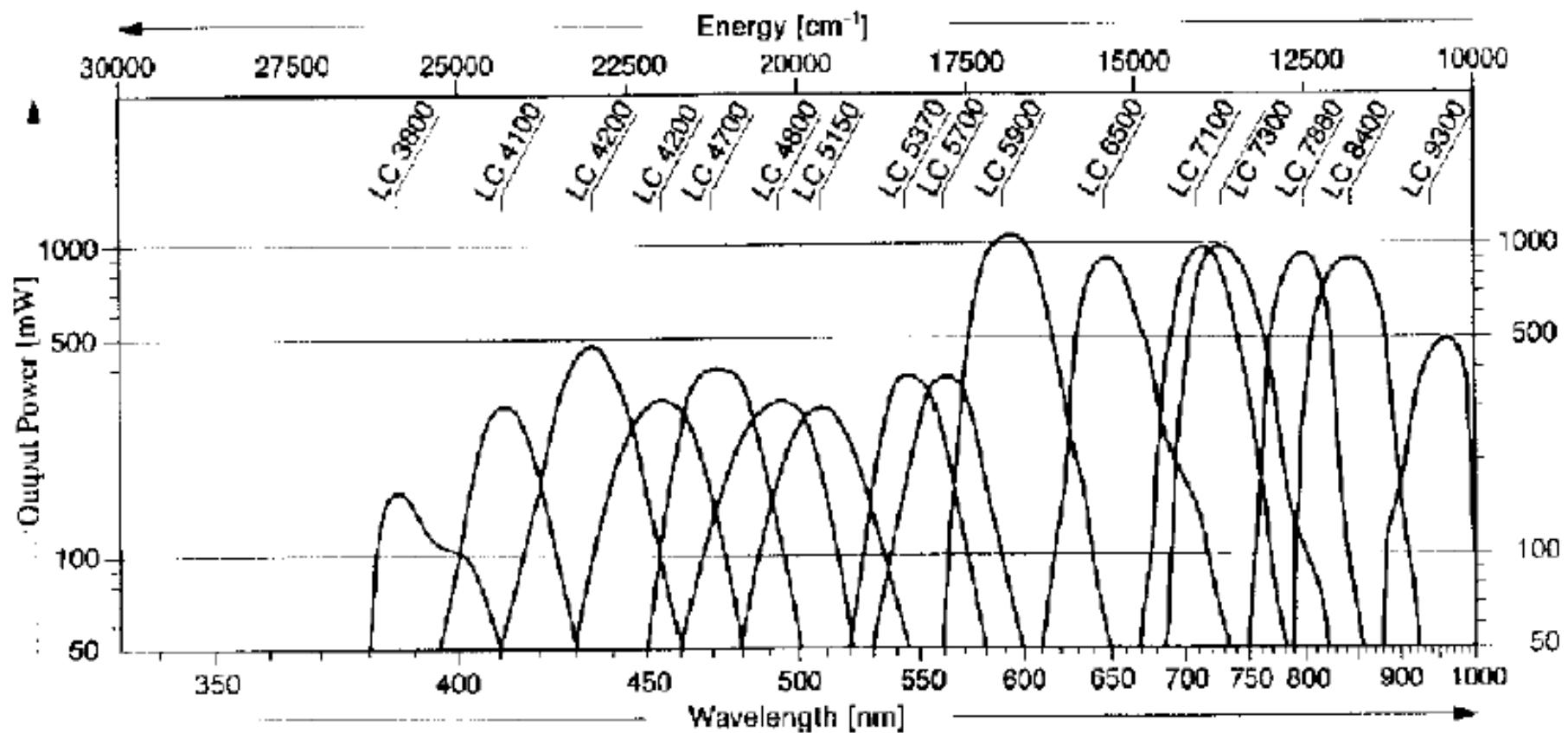
# Titanium:Sapphire laser

Sapphire  $\text{Al}_2\text{O}_3$  dotted with Ti ions

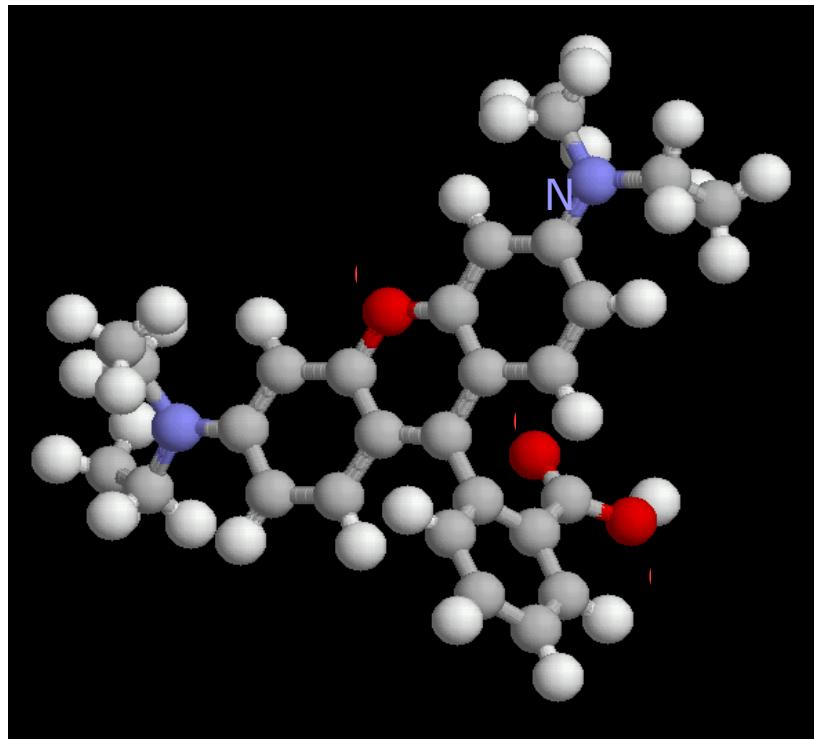
A vibronic solid state laser



# Liquid Dye Laser

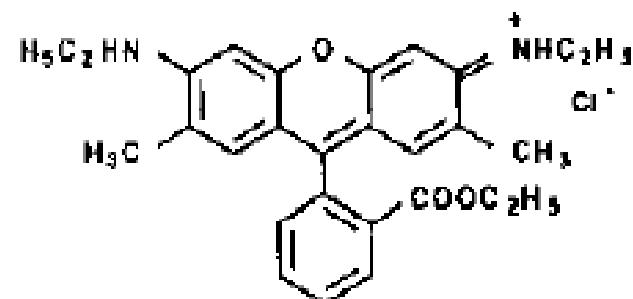


# Liquid Dye Laser



Rhodamine

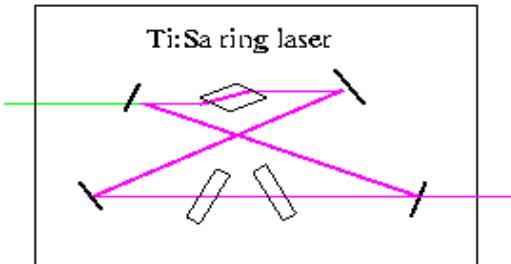
Rhodamine 6G



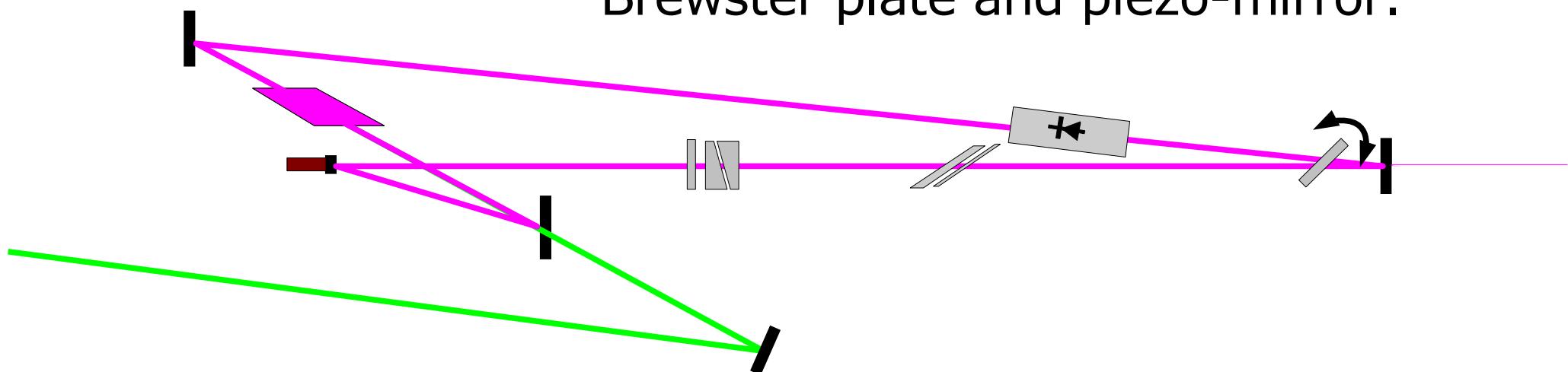
absorbs 532 nm

fluorescence  
555-585 nm

# Ti:Sa Ring Resonator



- Crystal pumped with 10 W Verdi
- Folded ring resonator
- Optical diode chooses light direction
- Gross wavelength selection with birefringent filter
- Single mode selection by a set of Fabry-Perot-etalons
- Scans and stabilization with Brewster plate and piezo-mirror.



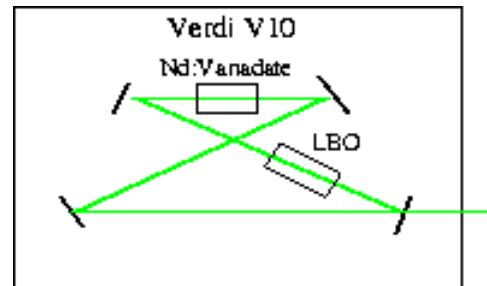
# Verdi

Neodymium Vanadate Nd:YVO<sub>4</sub>

Fundamental wavelength: 1064 nm

Intra cavity frequency doubling: 532 nm (2.33 eV)

Up to 10 W output power



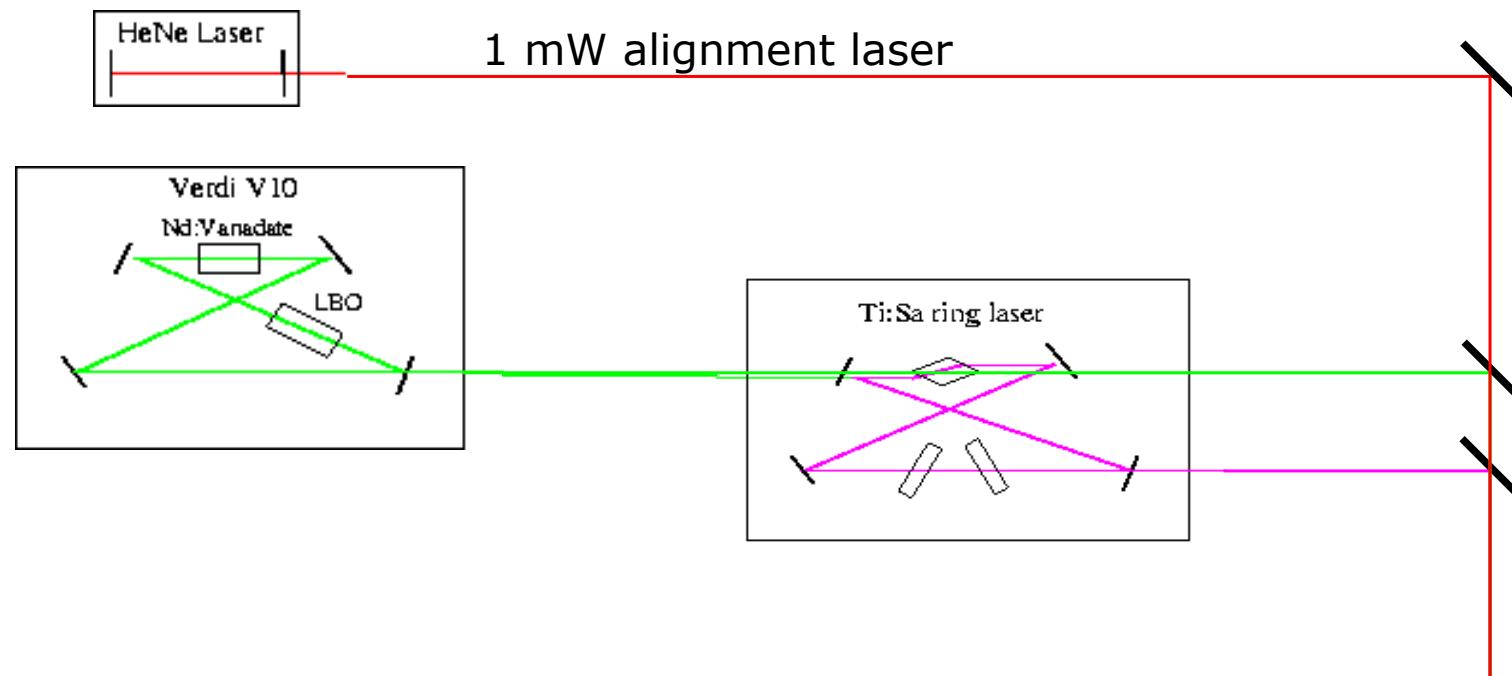
# Neodymium dotted solid state lasers

H															He			
Li	Be																	
Na	Mg																	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
Cs	Ba			Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra			Rf	Db	Sg	Bh	Hs	Mt	...	...	...						
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu				
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr				

Three 4f electrons



# Laser System at MAX II - I411

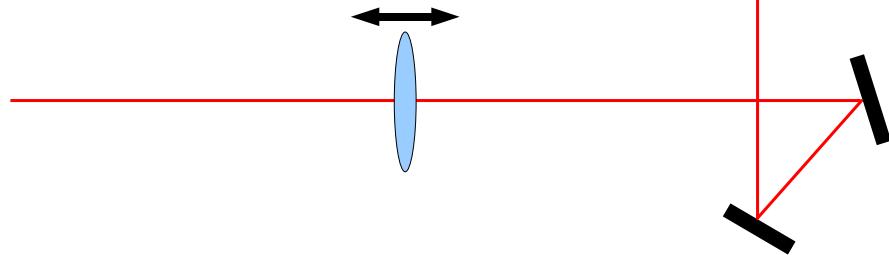


# Alignment Procedures



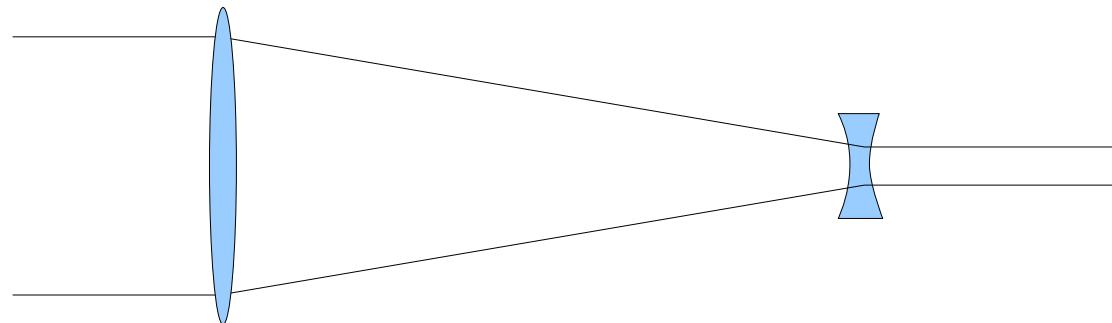
Four degrees of freedom specifying a laser beam:

- Position on the last mirror
- Direction to the target
- Spot size

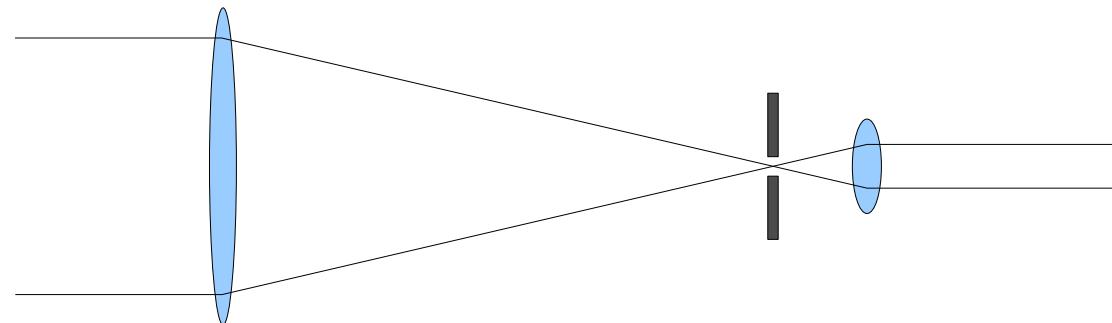


# Adjusting the Beam Diameter

- Galileo telescope



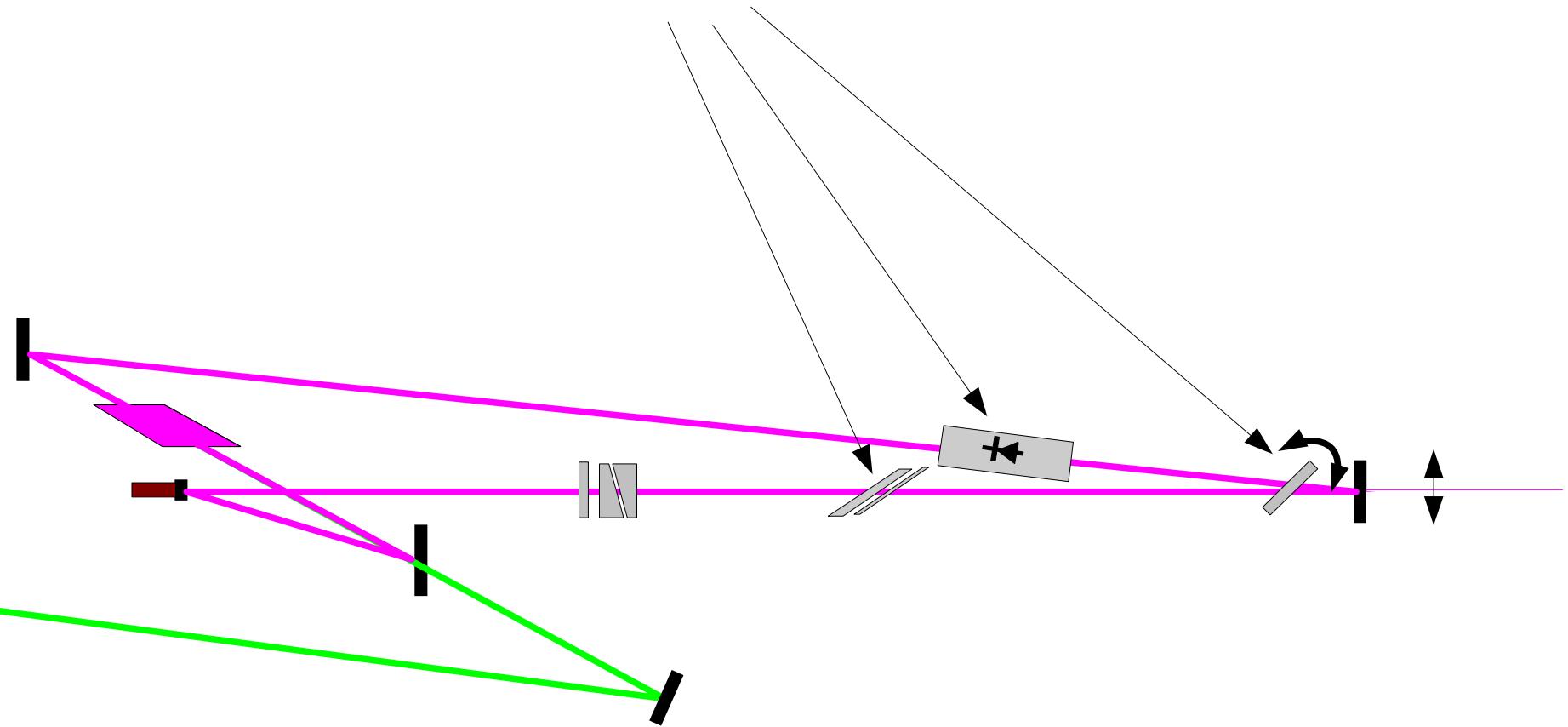
- Kepler telescope



- With pinhole: spacial filter

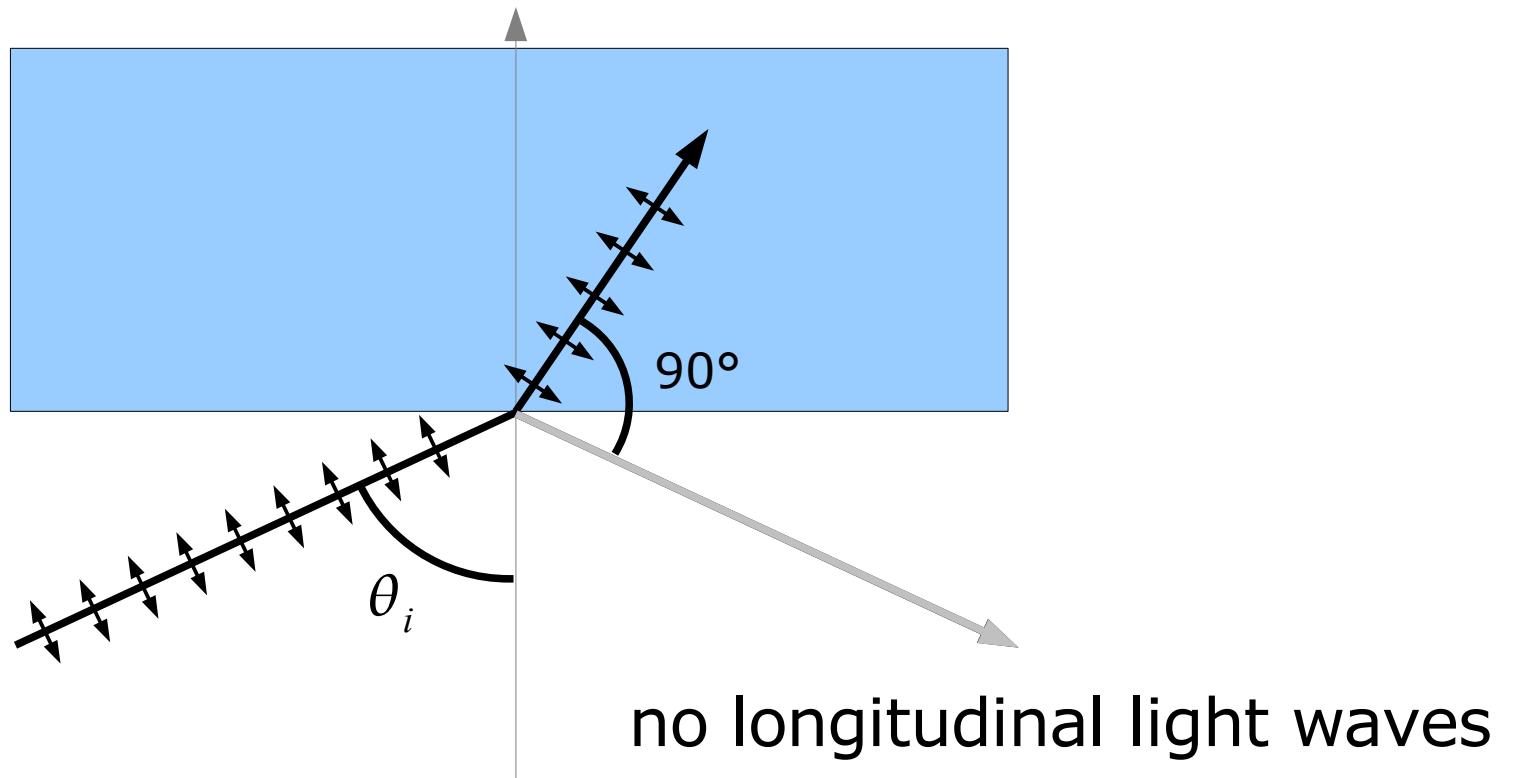
# Placing Windows with Low Losses

- vertical linear polarization
- all objects in Brewster Angle



# Brewster Angle

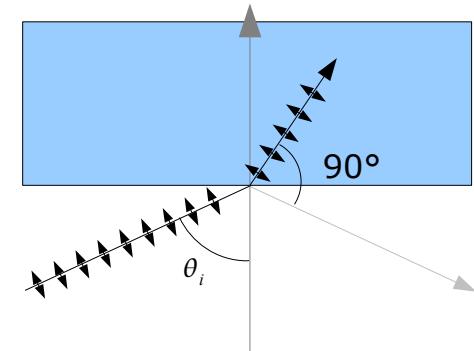
- No reflection for light polarized in plane of incidence.



# Brewster Angle

- No reflection for light polarized in plane of incidence.

- 1815 by David Brewster:  
 $\tan(\theta_i) = n$       For Glass  $\sim 56^\circ$



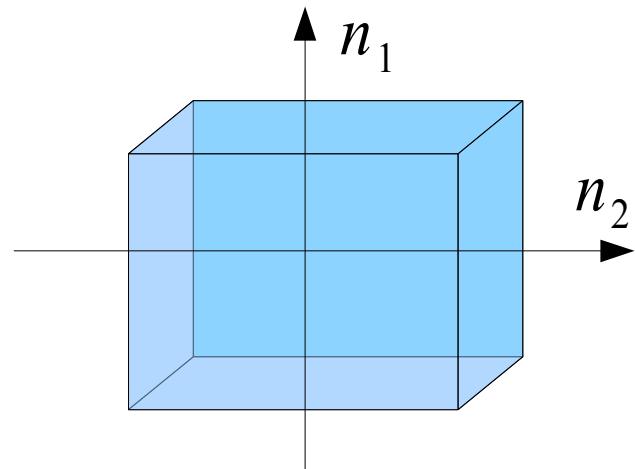
For classical optics:

- easy way to produce polarized light
- used in polarization crystals

For laser optics:

- no reflection losses for the parallel polarization
- defines the polarization of the laser mode

# Birefringence



different indexes of refraction

- for Quartz  $n_1=1.55$   $n_2=1.54$
- for Calcite  $n_1=1.49$   $n_2=1.66$

- retards one polarization with respect to the other
- $\lambda/2$  -retarding plate
  - flips linear polarization around the principal axis
- $\lambda/4$  -retarding plate
  - produces circularly polarized light

# Maxwell's equations

Gauß' Law

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

No magnetic monopoles

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

Faraday's law

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

Ampère's Law

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

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

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

# Polarization of the medium

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

No birefringence:  $\vec{P} = \epsilon_0 \chi \vec{E}$

$$\vec{D} = \epsilon_0 (1 + \chi) \vec{E} = \epsilon \vec{E}$$

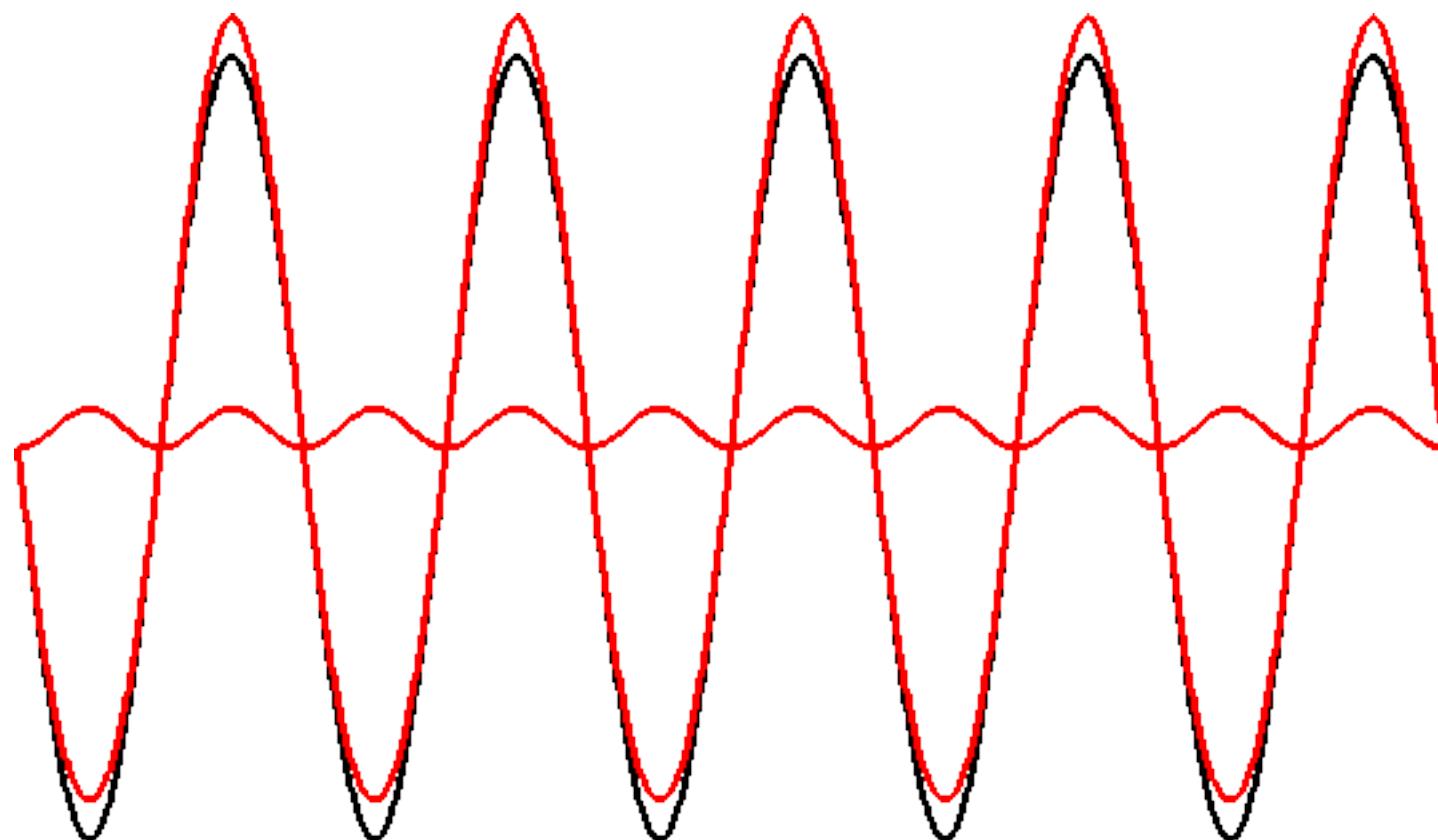
More general case:  $\chi$  is a tensor

$$P_i = \sum_{j=1,2,3} \epsilon_0 \chi_{ij} E_j$$

# Frequency doubling

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

$$\vec{P} = \epsilon_0 \chi \vec{E} + \vec{e} (2 \epsilon_0 \chi^{(2)} E^2 + \dots)$$



# More general case

$$\vec{E}^\omega(\vec{r}, t) = \frac{1}{2} [\vec{E}^\omega(\vec{r}, \omega) e^{i\omega t} + c.c.]$$

$$\vec{P}_{NL}^{2\omega}(\vec{r}, t) = \frac{1}{2} [\vec{P}^{2\omega}(\vec{r}, 2\omega) e^{2i\omega t} + c.c.]$$

$$P_i^{2\omega} = \sum_{j,k=1,2,3} \epsilon_0 d_{i,j,k}^{2\omega} E_j^\omega E_k^\omega$$