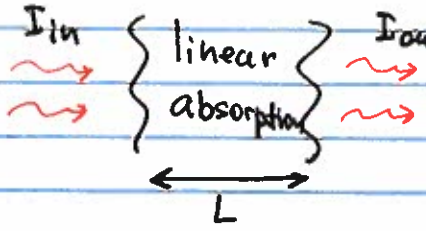
Nonlinear optics

When we talked about ray propagation, focusing and refraction, we never consider the effect of light intensity (brightness) on its behaviour

We assumed that all rays would reflect or refract exactly the same independently of their brightness. We also implied that the same fraction of light would be absorbed independently of its brightness

Linear optics regime: "output" light is linearly proportional to the "input" light



$I_{out} = e^{-\alpha L} I_{in}$

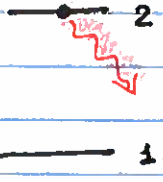
α - absorption coefficient

linear absorption doesn't depend on intensity I

Linear refractive index n does not depend on light intensity.

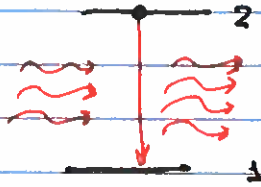
Non-linear optics: optical properties of the materials are light intensity dependent!

Stimulated emission is a nonlinear process



Spontaneous emission

Rate A (doesn't depend on I)

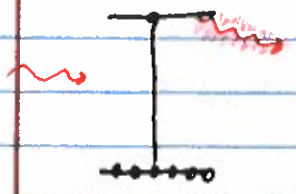


stimulated emission

Rate $B_{21} \cdot I^2$ higher at higher intensity

Because of that absorption for a weak and strong laser fields may be different

Weak field

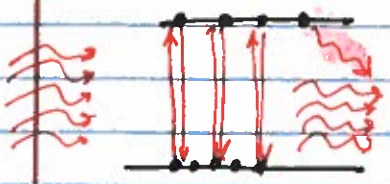


weak field.

- a photon comes and promotes one electron into the excited state.
- this electron soon returns to the ground state via spontaneous emission (likely)

large absorption

Strong field



- most atoms are engage in the stimulated absorption - emission cycle, only a few decay spontaneously so relative loss of energy from the laser field is weak → small absorption

Saturated absorption

$$\alpha(I) = \frac{\alpha_0}{1 + I/I_s}$$

I_s - saturation parameter (depends on the specific system)

Nonlinear refractive index

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

higher intensity → stronger index → change in refractive

That means that if a laser beam has intensity distribution (stronger in the middle, weaker on the sides) it can "create" its own lens

→ self-focusing

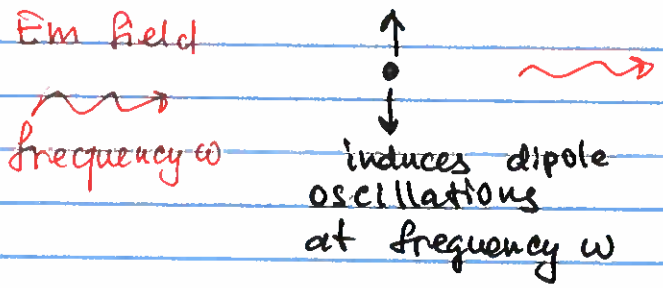
— self-defocusing

This variation of refractive index can even create a waveguide

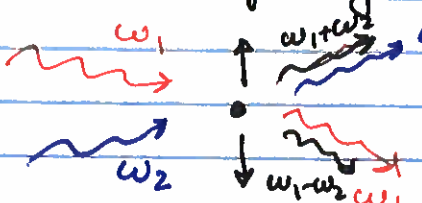
← ~~for example~~

Frequency conversion in nonlinear processes

Linear interaction model

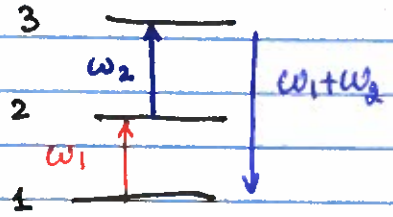


What if we send two fields of different frequency?



dipole starts moving in a complex manner consisting of oscillations at ω_1, ω_2, $\omega_1+\omega_2$, $\omega_1-\omega_2$ (new frequencies!)

Atomic level representation: atom absorbs one photon of frequency 1 and 1 photon of frequency 2, and releases the energy in one photon frequency $\omega_1+\omega_2 = \omega_{new}$



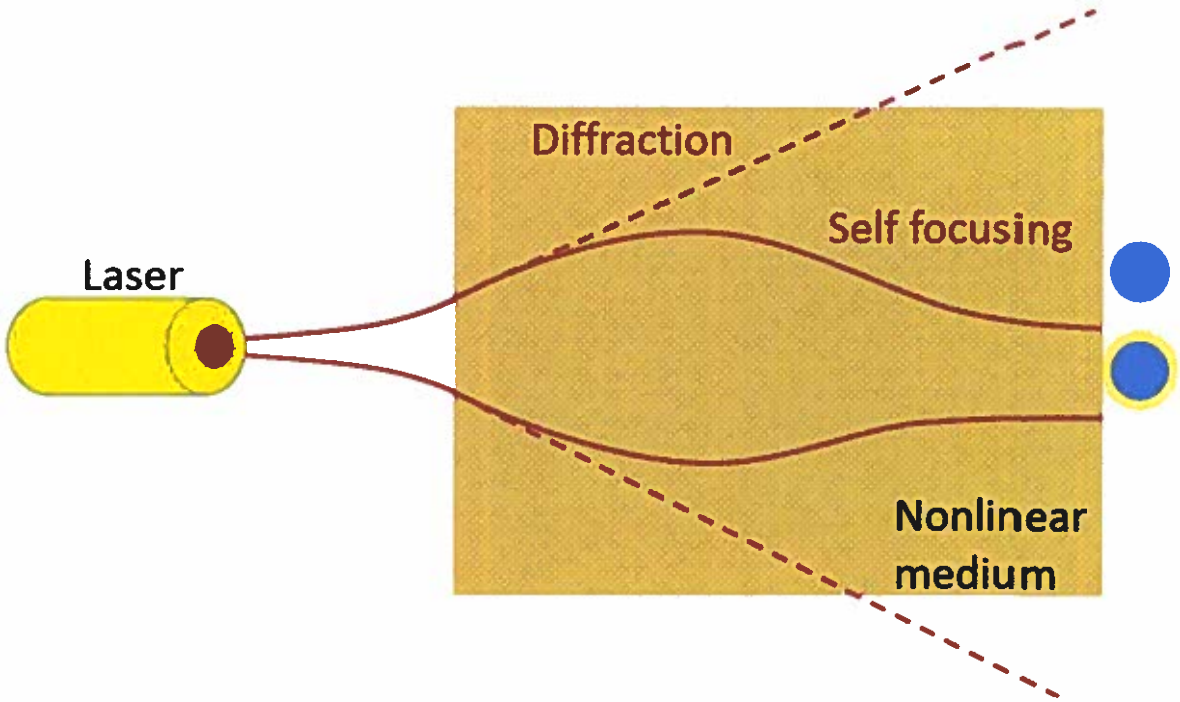
Energy conservation $\hbar\omega_1 + \hbar\omega_2 = \hbar(\omega_1+\omega_2) = \hbar\omega_{new}$

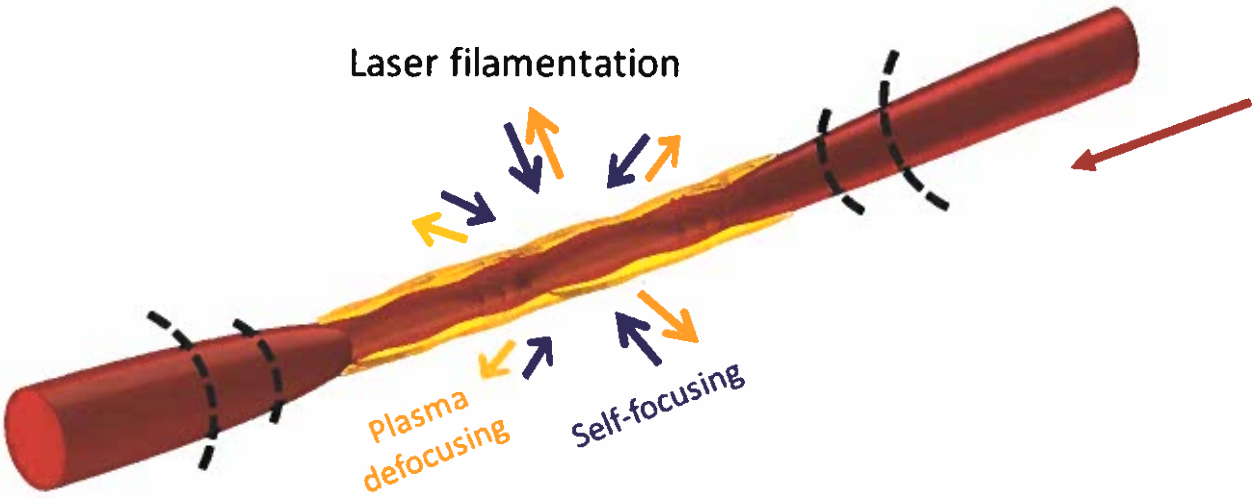
$$\frac{2\pi\hbar c}{\lambda_1} + \frac{2\pi\hbar c}{\lambda_2} = \frac{2\pi\hbar c}{\lambda_{new}}$$

if $\lambda_1 = 800nm$ and $\lambda_2 = 400nm$

$$\frac{1}{\lambda_{new}} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} = \frac{1}{800nm} + \frac{1}{400nm} = \frac{3}{800nm}$$

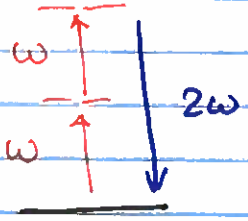
$$\lambda_{new} = \frac{800nm}{3} = 266nm$$


Diffraction
Self focusing
Laser
Nonlinear
medium


Laser filamentation
Plasma
defocusing
Self-focusing

Different nonlinear processes

Second harmonic generation $\omega + \omega = 2\omega$



$$\lambda_{generated} = \frac{\lambda}{2}$$

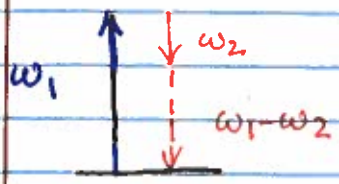
All green laser pointers are green, because they have a 1064 nm infrared laser whose frequency get doubled in a nonlinear crystal

$\lambda_{green} = 532nm = \frac{1}{2}\lambda_{IR} = \frac{1}{2} \cdot 1064nm$

Sum and Difference Frequency generation

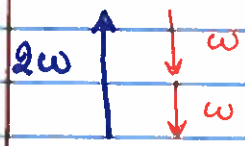


Sum frequency: two photons are converted in a single photon of $(\omega_1+\omega_2)$, higher, frequency



Difference frequency: single high-frequency photons "is "broken" into two by emitting one photon into the second field (ω_2) and the other of their frequency difference

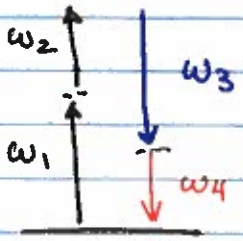
Parametric down conversion



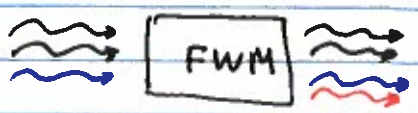
One higher-energy photons splits into two "twins" of the same frequency

Working horse of quantum information for generating entangled photons (and single-photon sources)

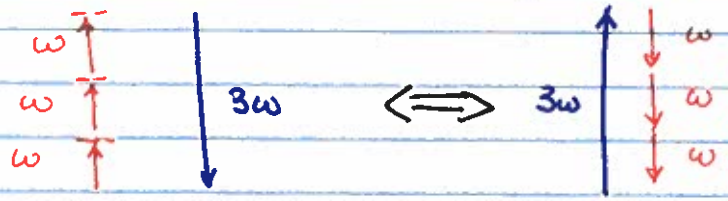
Nonlinear processes can involve more than three photons (actually, having even number of photons is easier



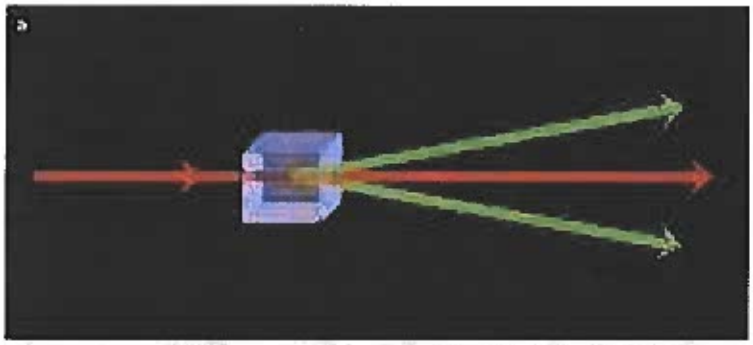
Four-wave mixing

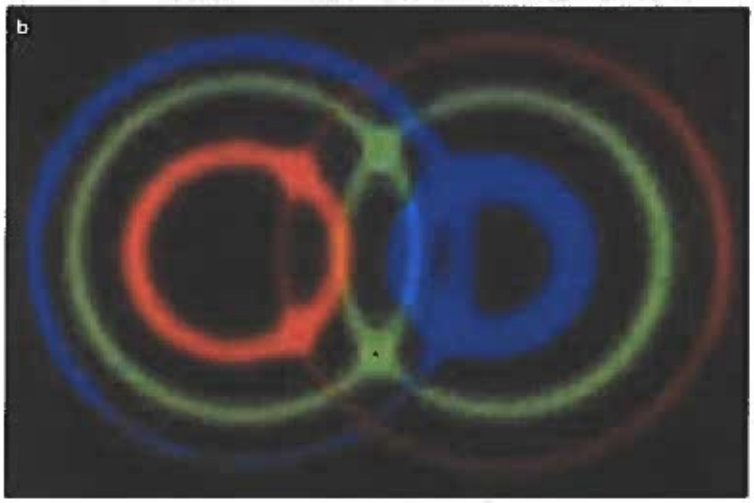


Third harmonics generation






a


b