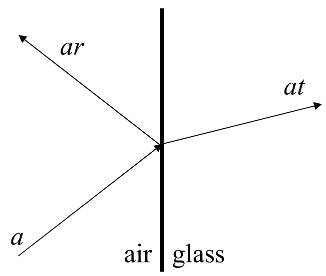
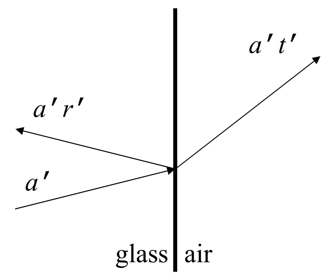
Today's summary

- Multiple beam interferometers: Fabry-Perot resonators
  - Stokes relationships
  - Transmission and reflection coefficients for a dielectric slab
  - Optical resonance
- Principles of lasers
- Coherence: spatial / temporal

Fabry-Perot interferometers

Relation between *r*, *r′* and *t*, *t′*





$r' = -r$

$r^2 + tt' = 1$

Stokes relationships

Proof: algebraic from the Fresnel coefficients or using the property of *preservation of the field properties upon time reversal*

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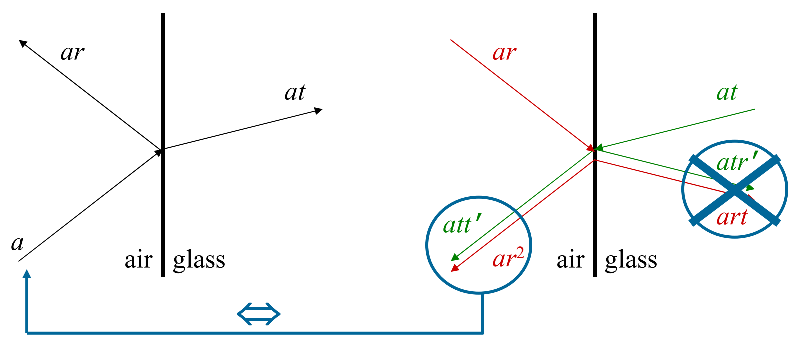
Proof using time reversal



$$a(r + r')t = 0 \Rightarrow r = -r'$$

$$a(r^2 + tt') = a \Rightarrow r^2 + tt' = 1$$

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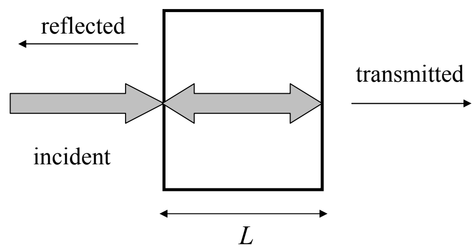
Fabry-Perot Interferometer



Resonance condition: reflected wave = 0

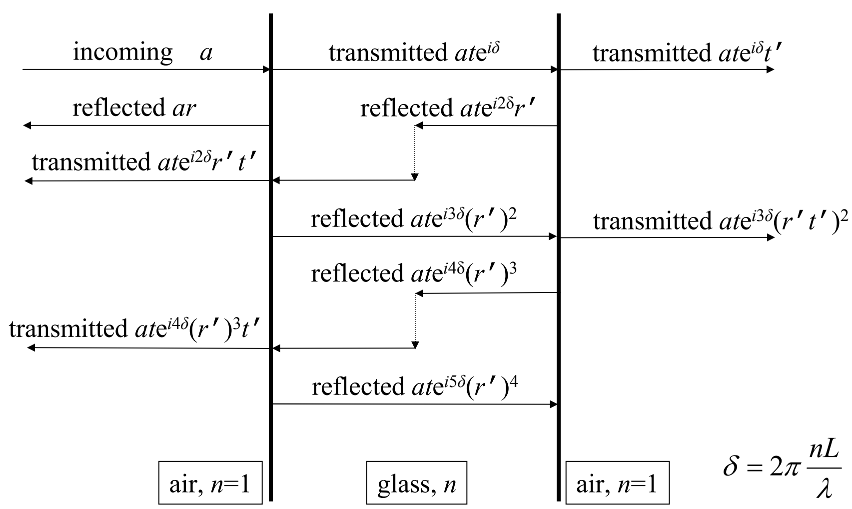
⇔ all reflected waves interfere destructively

$$L = \frac{m\lambda}{2n}$$

$m\lambda$ ← wavelength in free space

$2n$ ← refractive index

Calculation of the reflected wave



$$\delta = 2\pi\frac{nL}{\lambda}$$

Calculation of the reflected wave

$$a_{\text{reflected}} = a\left\{r + tt'r'\,\mathrm{e}^{i2\delta}\left(1 + r'^2\,\mathrm{e}^{i2\delta} + r'^4\,\mathrm{e}^{i4\delta} + \cdots\right)\right\}$$

$$= a\left\{r + tt'r'\,\mathrm{e}^{i2\delta}\,\frac{1}{1 - r'^2\,\mathrm{e}^{i2\delta}}\right\}$$

Use Stokes relationships

$$r' = -r$$
$$r^2 + tt' = 1$$

$$a_{\text{reflected}} = a\,\frac{r\left(1 - \mathrm{e}^{i2\delta}\right)}{1 - r^2\,\mathrm{e}^{i2\delta}}$$

Transmission & reflection coefficients

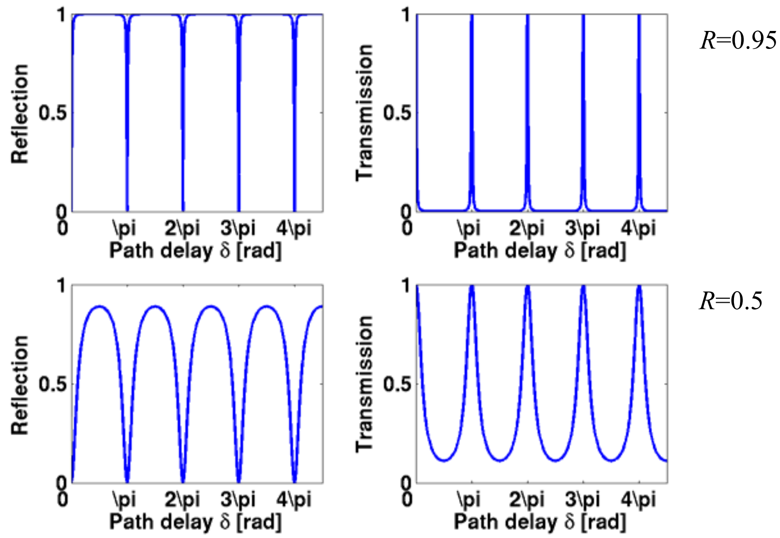
$$a_{\text{reflected}} = a\,\frac{\left(1 - \mathrm{e}^{i2\delta}\right)r}{1 - r^2\,\mathrm{e}^{i2\delta}} \qquad a_{\text{transmitted}} = a\,\frac{tt'}{1 - r^2\,\mathrm{e}^{i2\delta}}$$

$$R \equiv |r|^2$$

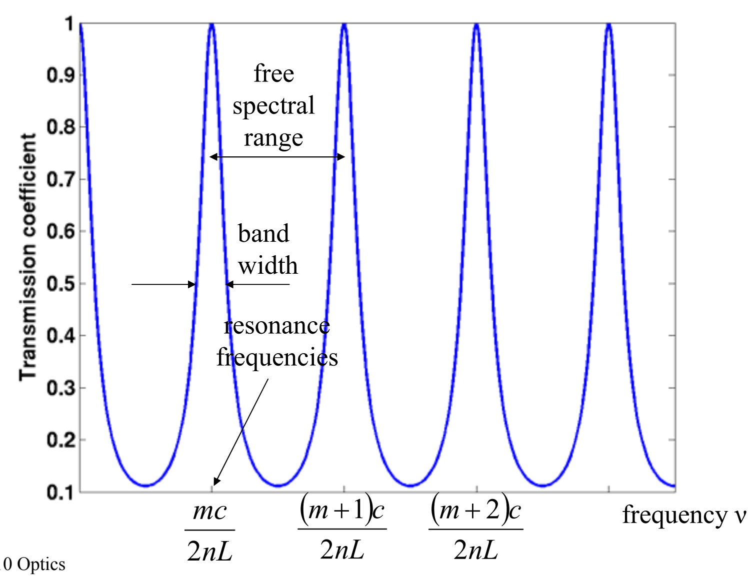
$$\begin{pmatrix}\text{reflection}\\ \text{coefficient}\end{pmatrix} = \left|\frac{a_{\text{reflected}}}{a}\right|^2 = \frac{4R\sin^2\delta}{(1-R)^2 + 4R\sin^2\delta}$$

$$\begin{pmatrix}\text{transmission}\\ \text{coefficient}\end{pmatrix} = \left|\frac{a_{\text{transmitted}}}{a}\right|^2 = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2\delta}$$

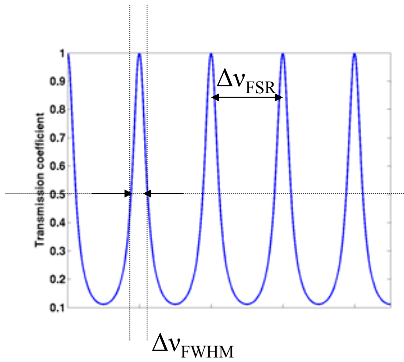
Transmission & reflection *vs* path



Fabry-Perot terminology



Fabry-Perot terminology



FWHM Bandwidth is inversely proportional to the *finesse* ***F*** (or *quality factor*) of the cavity

$$F \equiv \frac{\pi\sqrt{R}}{1-R}$$

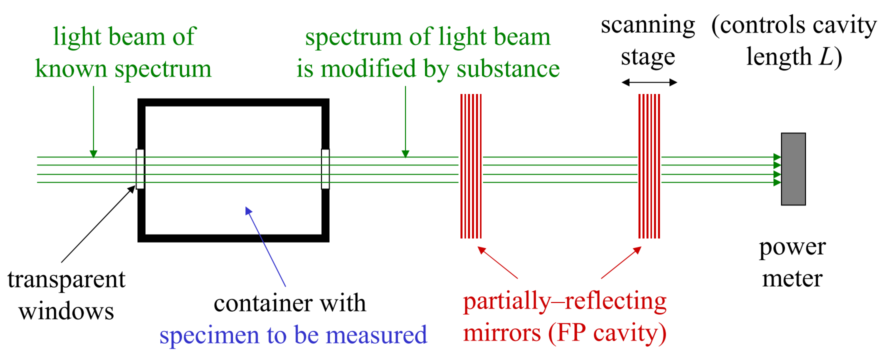
$$\Delta\nu_{\text{FWHM}} = \frac{c}{2nLF}$$

$$\Delta\nu_{\text{FWHM}} = \frac{\Delta\nu_{\text{FSR}}}{F} \qquad (\text{bandwidth}) = \frac{(\text{free spectral range})}{(\text{finesse})}$$

Spectroscopy using Fabry-Perot cavity

Goal: to measure the specimen's absorption as function of frequency ω

Experimental measurement principle:



Spectroscopy using Fabry-Perot cavity

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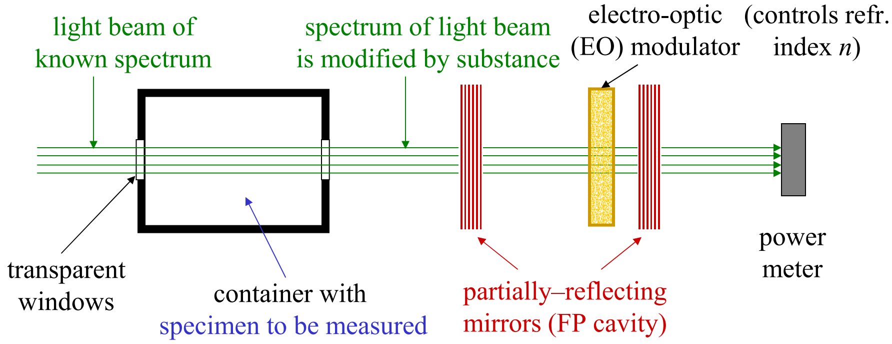

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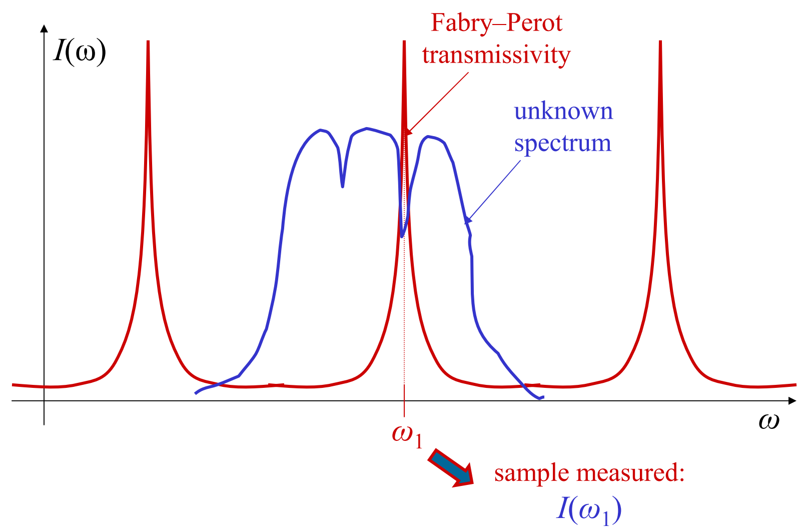
Spectroscopy using Fabry-Perot cavity



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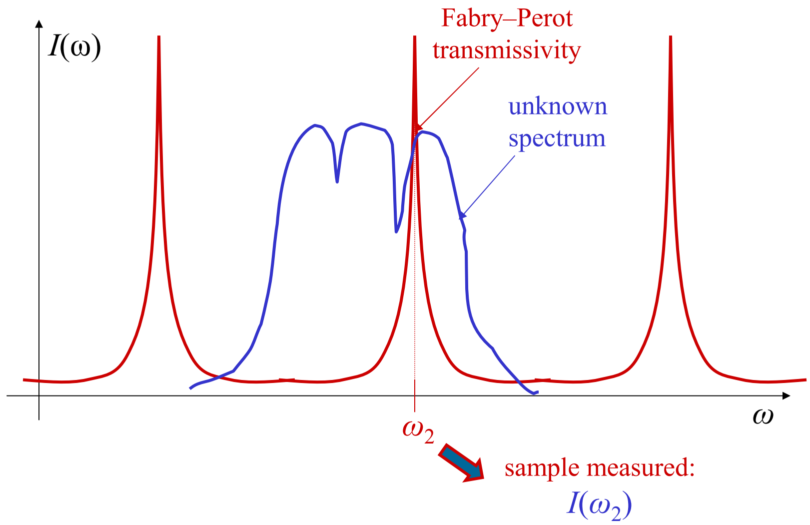
Spectroscopy using Fabry-Perot cavity



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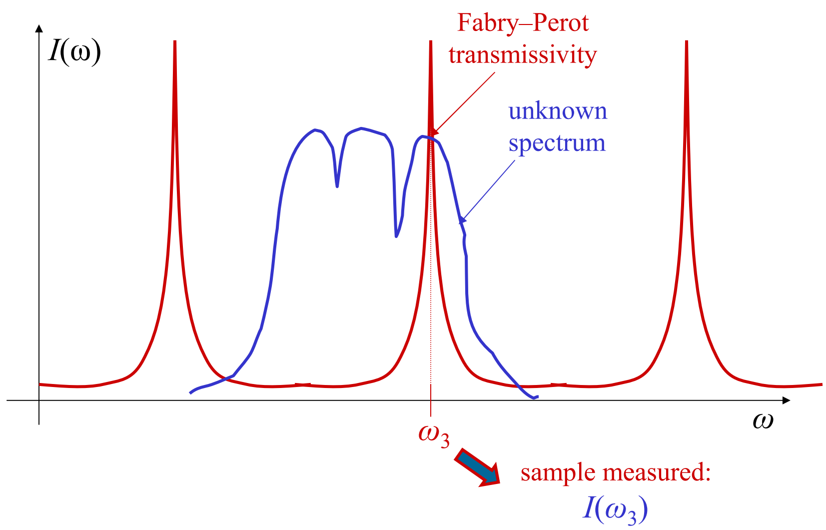
Spectroscopy using Fabry-Perot cavity



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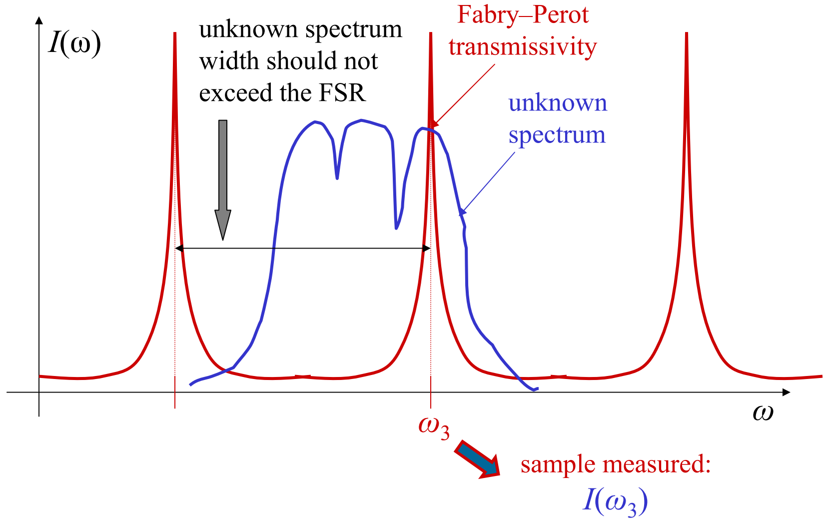
Spectroscopy using Fabry-Perot cavity



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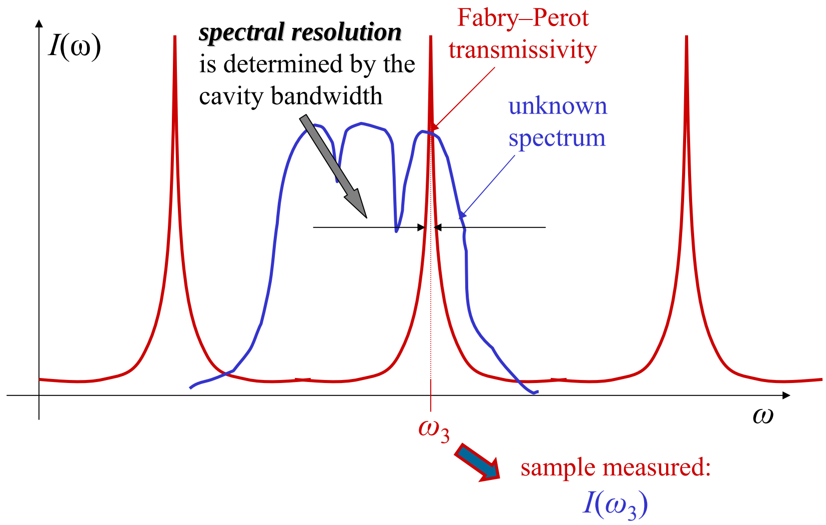
Spectroscopy using Fabry-Perot cavity



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Lasers

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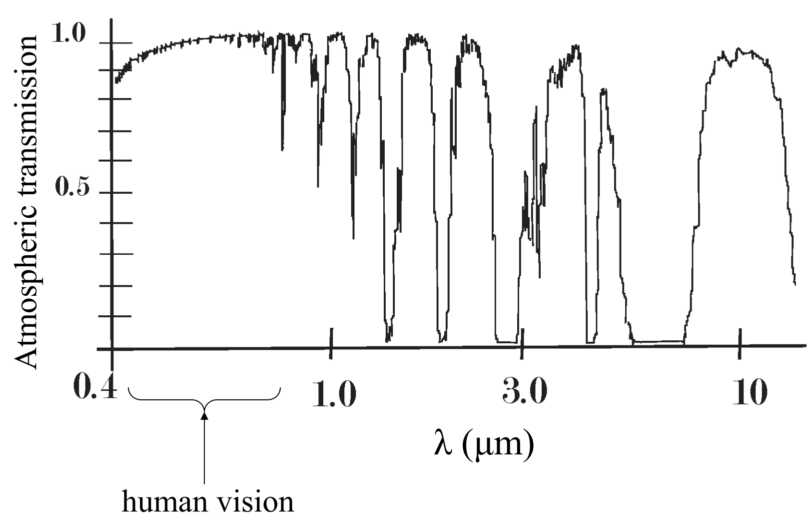
Absorption spectra



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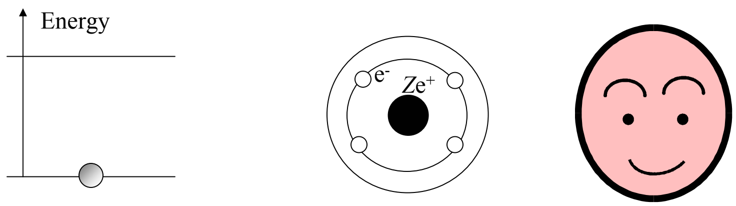
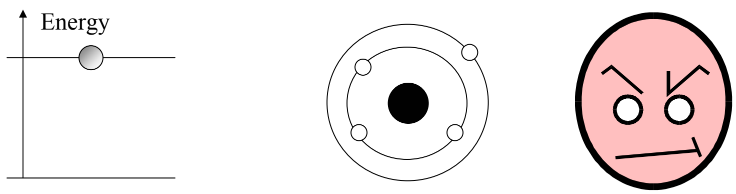
Semi-classical view of atom excitations

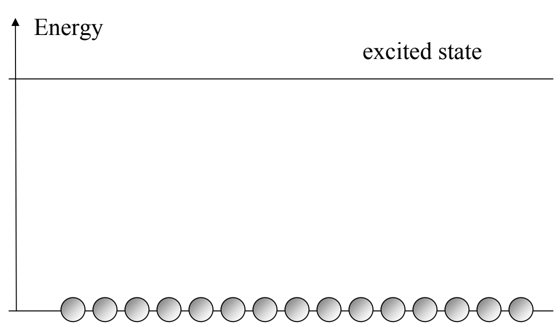


Atom in ground state



Atom in excited state

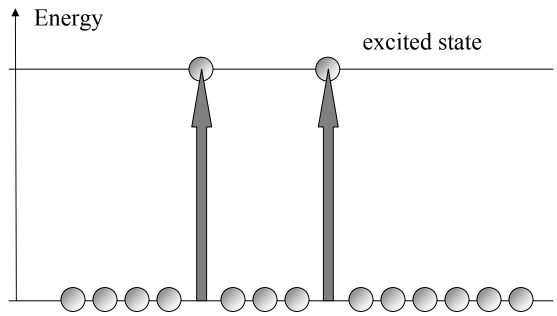
Light generation



equilibrium: most atoms in ground state

ground state

Light generation



A **pump** mechanism (e.g. thermal excitation or gas discharge) ejects some atoms to the excited state

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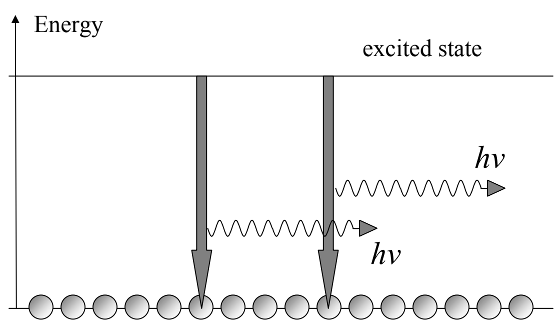
Light generation



The excited atoms **radiatively decay**, emitting one photon each

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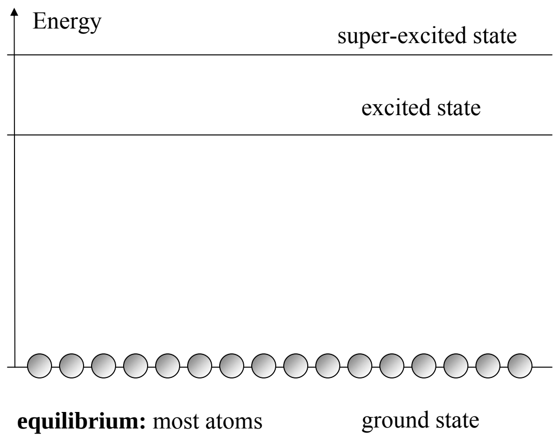
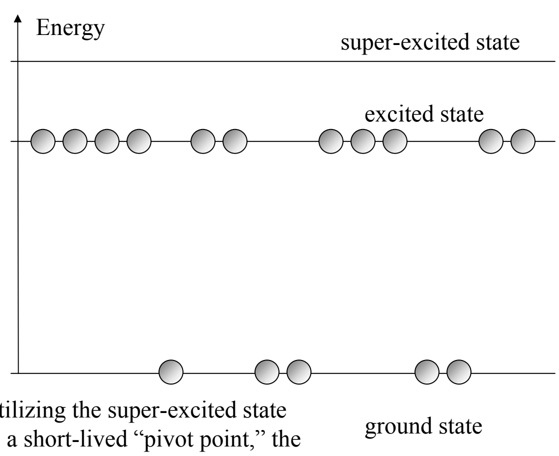
Light amplification: 3-level system



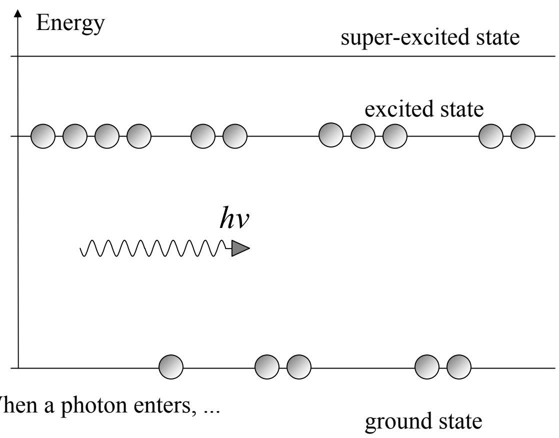
equilibrium: most atoms in ground state; note the existence of a third, “super-excited” state

Light amplification: 3-level system



Utilizing the super-excited state as a short-lived “pivot point,” the pump creates a **population inversion**

Light amplification: 3-level system



When a photon enters, ...

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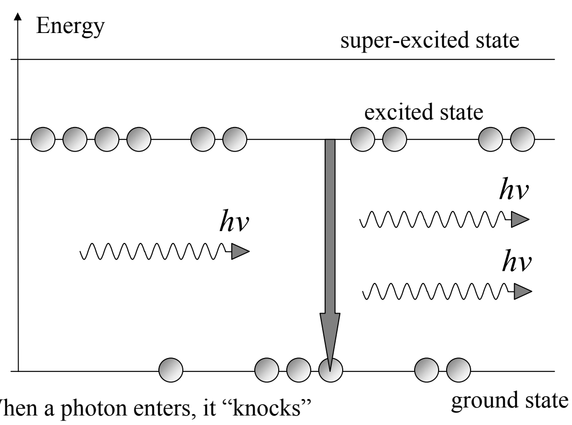
Light amplification: 3-level system



When a photon enters, it "knocks" an electron from the inverted population down to the ground state, thus creating a new photon. This amplification process is called **stimulated emission**

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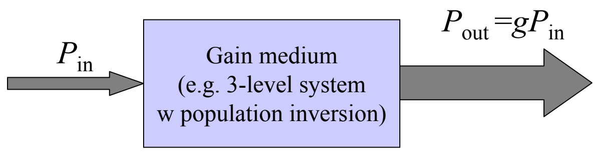
Light amplifier



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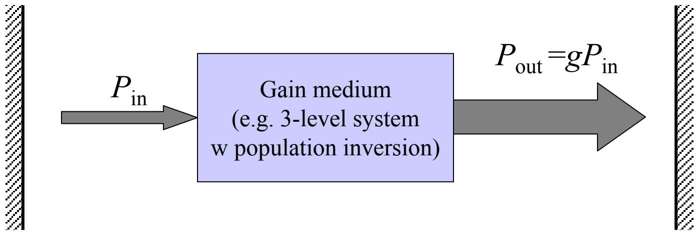
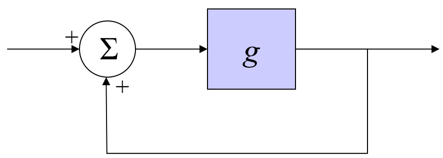
Light amplifier w positive feedback



When the gain exceeds the roundtrip losses, the system goes into **oscillation**



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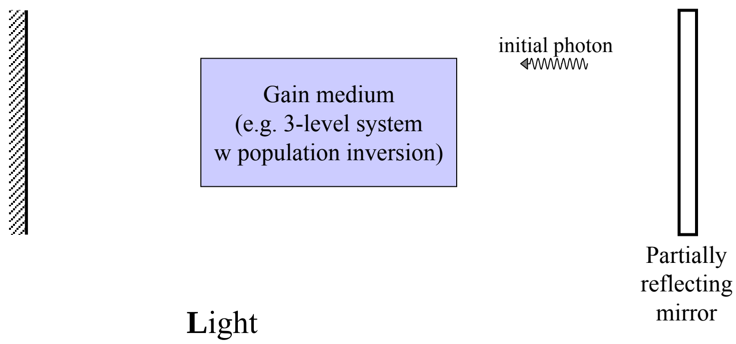
Laser



Light
Amplification through
Stimulated
Emission of
Radiation

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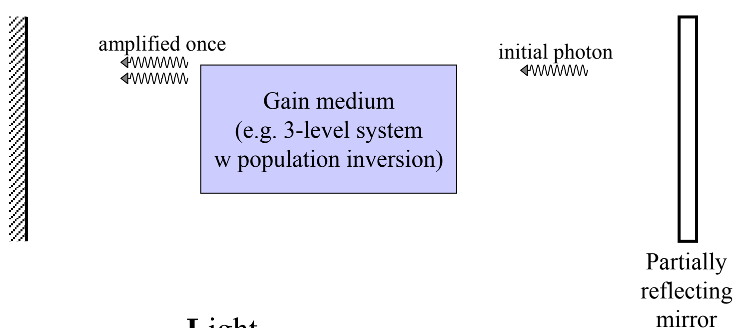
Laser



Light
Amplification through
Stimulated
Emission of
Radiation

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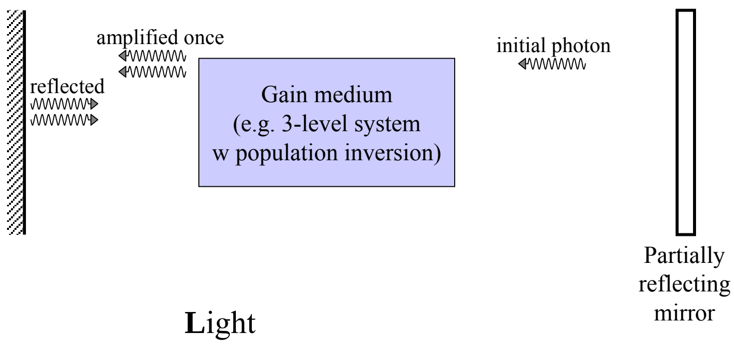
Laser



Light
Amplification through
Stimulated
Emission of
Radiation

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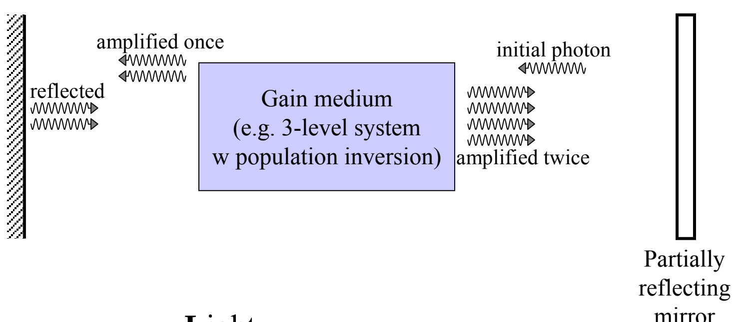
Laser



Light
Amplification through
Stimulated
Emission of
Radiation

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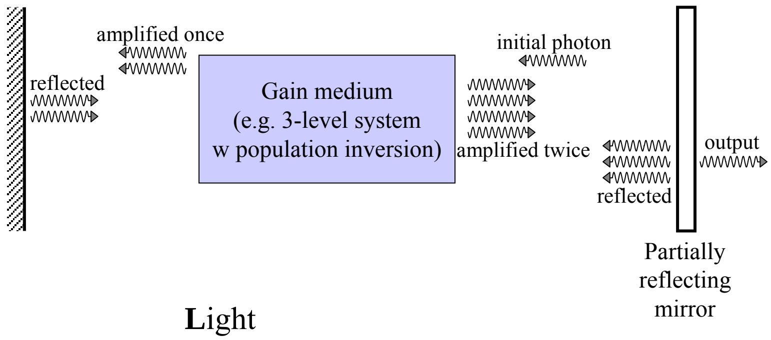
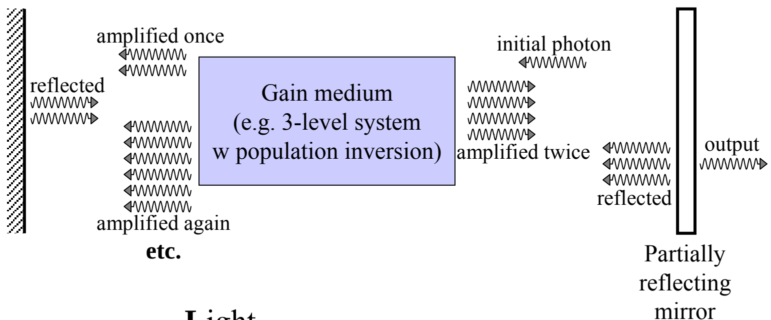
Laser



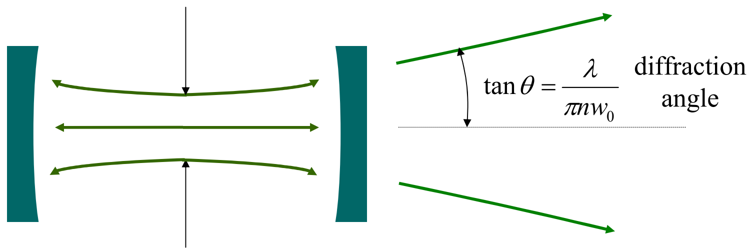
Light
Amplification through
Stimulated
Emission of
Radiation

Laser



Light
Amplification through
Stimulated
Emission of
Radiation

Confocal laser cavities



Beam profile:
2D Gaussian function

"TE_{00} mode"

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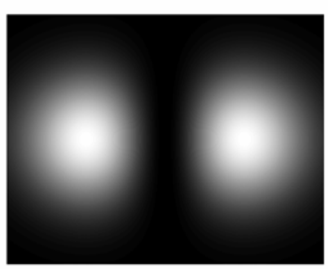
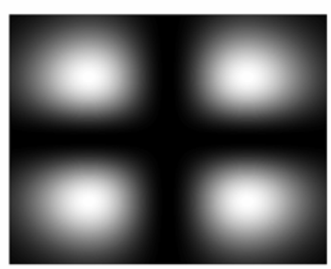
Other "transverse modes"



TE10



TE11

(usually undesirable)

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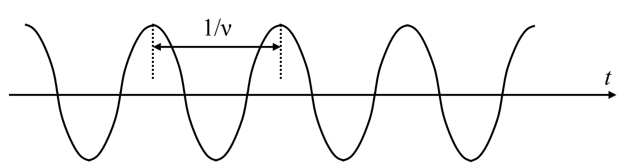
Types of lasers

- Continuous wave (cw)
- Pulsed
  - Q-switched
  - mode-locked

- Gas (Ar-ion, HeNe, CO_2)
- Solid state (Ruby, Nd:YAG, Ti:Sa)
- Diode (semiconductor)
- Vertical cavity surface-emitting lasers –VCSEL– (also sc)
- Excimer (usually ultra-violet)

CW (continuous wave lasers)

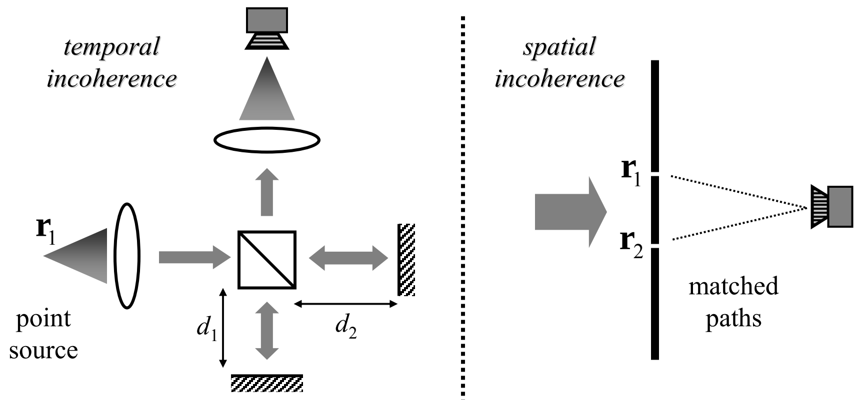
Laser oscillation well approximated by a sinusoid



Typical sources:
• Argon-ion: 488nm (blue) or 514nm (green); power ~1-20W
• Helium-Neon (HeNe): 633nm (red), also in green and yellow; ~1-100mW
• doubled Nd:YaG: 532nm (green); ~1-10W

Quality of sinusoid maintained over a time duration known as
"coherence time" t_c
Typical coherence times ~20nsec (HeNe), ~10μsec (doubled Nd:YAG)

Two types of incoherence



Michelson interferometer | Young interferometer

poly-chromatic light
(=multi-color, broadband)

mono-chromatic light
(= single color, narrowband)

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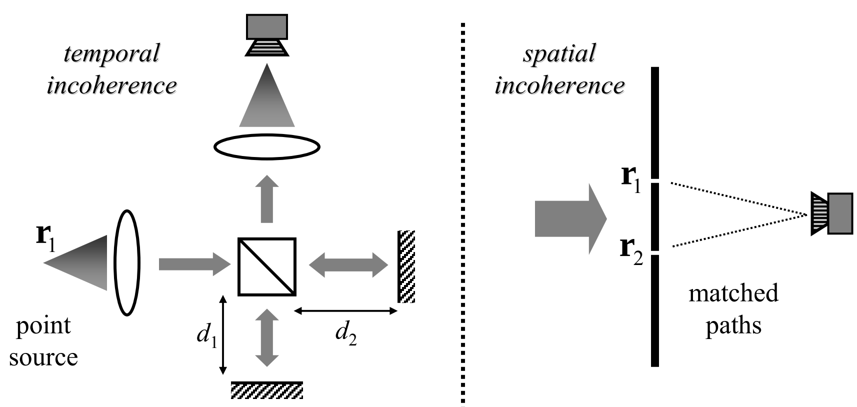
Two types of incoherence



waves from unequal paths
do not interfere

waves with equal paths
but from different points
on the wavefront
do not interfere

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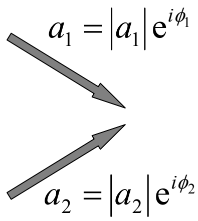
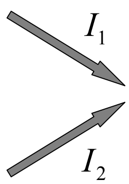
Coherent vs incoherent beams



<u>Mutually coherent</u>: superposition field *amplitude* is described by *sum of complex amplitudes*

$$a = a_1 + a_2 = |a_1| e^{i\phi_1} + |a_2| e^{i\phi_2}$$

$$I = |a|^2 = |a_1 + a_2|^2$$



<u>Mutually incoherent</u>: superposition field *intensity* is described by *sum of intensities*

$$I = I_1 + I_2$$

(the phases of the individual beams vary randomly with respect to each other; hence, we would need statistical formulation to describe them properly — *<u>statistical optics</u>*)

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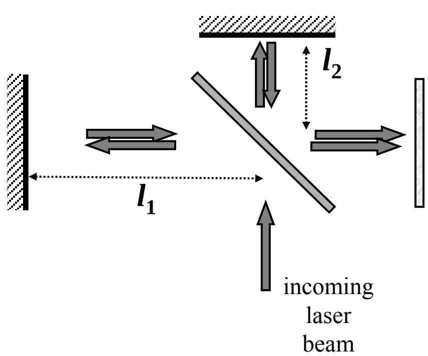
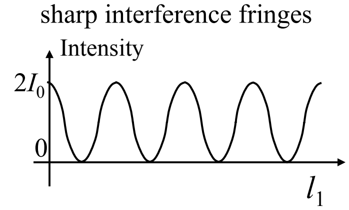
Coherence time and coherence length

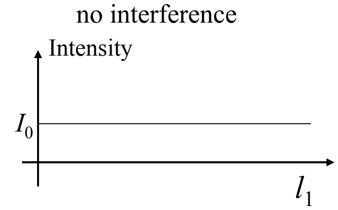


Michelson interferometer

• l_1-l_2 much shorter than "coherence length" ct_c
sharp interference fringes



• l_1-l_2 much longer than "coherence length" ct_c
no interference



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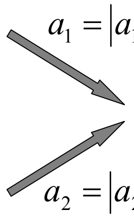
Coherent vs incoherent beams



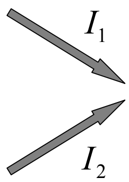
$a_1 = |a_1| e^{i\phi_1}$

$a_2 = |a_2| e^{i\phi_2}$

<u>Coherent</u>: superposition field *amplitude* is described by *sum of complex amplitudes*

$$a = a_1 + a_2 = |a_1| e^{i\phi_1} + |a_2| e^{i\phi_2}$$

$$I = |a|^2 = |a_1 + a_2|^2$$



I_1

I_2

<u>Incoherent</u>: superposition field *intensity* is described by *sum of intensities*

$$I = I_1 + I_2$$

(the phases of the individual beams vary randomly with respect to each other; hence, we would need statistical formulation to describe them properly — *<u>statistical optics</u>*)

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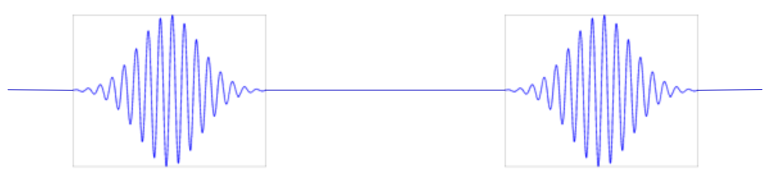
Mode-locked lasers



Typical sources: Ti:Sa lasers (major vendors: Coherent, Spectra Phys.)
Typical mean wavelengths: 700nm – 1.4µm (near IR)
can be doubled to visible wavelengths
or split to visible + mid IR wavelengths using OPOs or OPAs
(OPO=optical parametric oscillator;
OPA=optical parametric amplifier)
Typical pulse durations: ~psec to few fsec
(just a few optical cycles)
Typical pulse repetition rates (“rep rates”): 80-100MHz
Typical average power: 1-2W; peak power ~MW-GW

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Overview of light sources

<u>non-Laser</u>

Thermal: polychromatic, spatially incoherent (e.g. light bulb)

Gas discharge: monochromatic, spatially incoherent (e.g. Na lamp)

Light emitting diodes (LEDs): monochromatic, spatially incoherent

<u>Laser</u>

Continuous wave (or cw): strictly monochromatic, spatially coherent (e.g. HeNe, Ar^+, laser diodes)

Pulsed: quasi-monochromatic, spatially coherent (e.g. Q-switched, mode-locked)

~nsec ~psec to few fsec

pulse duration

mono/poly-chromatic = single/multi color

MIT 2.71/2.710 Optics
10/24/05 wk8-a-47