Pumping

Two main pumping mechanisms: optical and electrical pumping.

1. Optical pumping:

- **Incoherent sources** (lamps): it is typically used for solid-state lasers (Nd, ruby…) or dye lasers, for which the line broadening is significant and thus it si possible to pump on wide bands.

- **Coherent sources** (lasers): the active medium to be pumped has to have an absorption line matching the emission line of the pumping laser (es. Ti:sapphire can be pumped with the SH of a Nd:YAG laser @ 532 nm)

2. Electrical pumping:

It can be obtained giving strong electrical discharges to the active medium.
It is typically used for gas or semiconductors (diode) lasers

Pumping

Other pumping mechanisms are:

- **Pumping with x-rays**
- **Pumping with electron beams**

not much used, setups very expensive

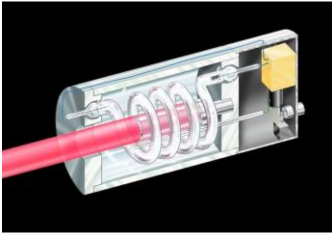
- **Chemical pumping**: it is obtained exploiting exothermal chemical reactions (which leave the active medium in an excited state)
- **Gas dynamic pumping**: supersonic gas expansion

They are used for very high-power lasers: by chemical pumping it was obtained the MIRACL – Mid-IR Advanced Chemical Laser (2.2 MW in cw!)

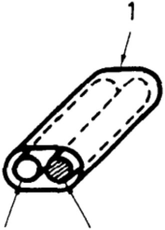
Typically used for military purposes.

Optical pumping

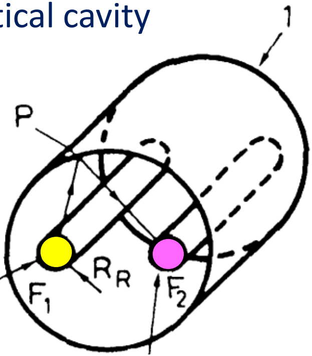
Spiral lamp

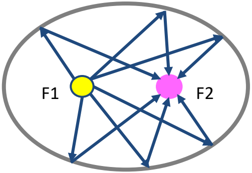


Close coupling



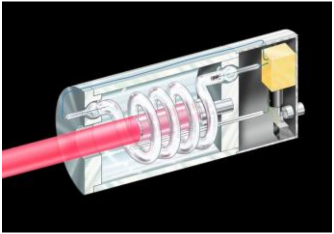
Elliptical cavity



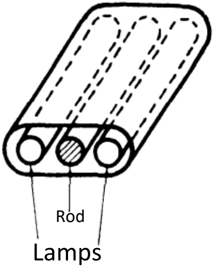


Optical pumping

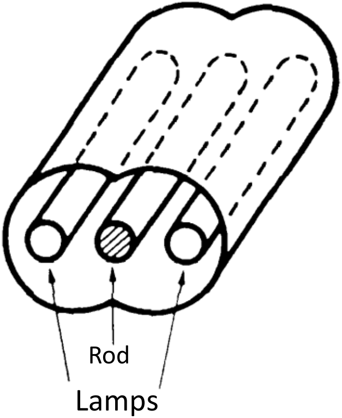
Spiral lamp



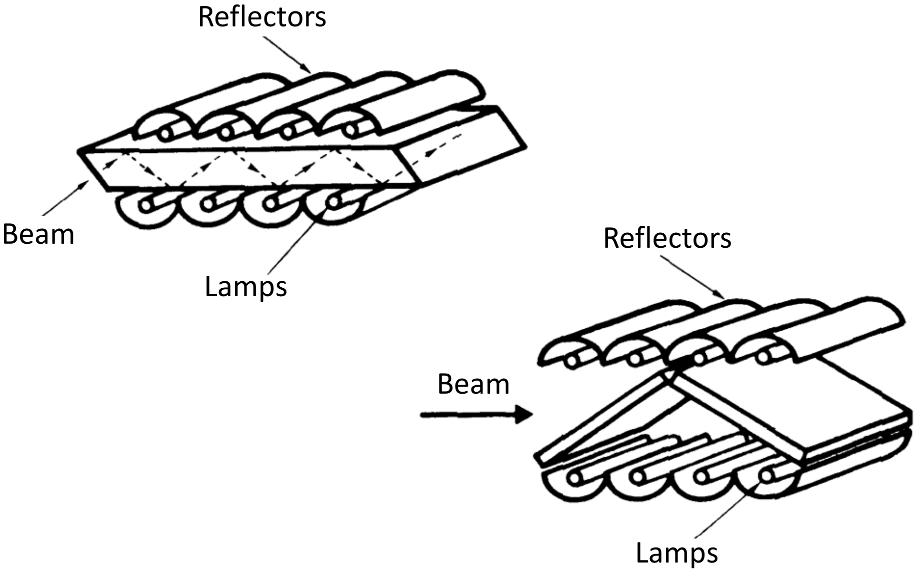
Close coupling



Double-elliptical cavity



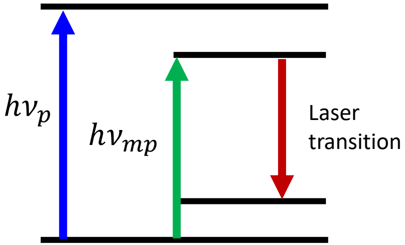
Optical pumping



Optical pumping

Pumping rate

$$\left(\frac{dN_2}{dt}\right)_p = R_p = W_p N_g$$



Pumping efficiency

$$\boxed{\eta_p = \eta_r \eta_t \eta_a \eta_{pq}}$$

$$\boxed{\eta_p = \frac{P_m}{P_p} = \frac{R_p A l h\nu_{mp}}{P_p}}$$

η_r = radiative efficiency

η_t = transfer efficiency

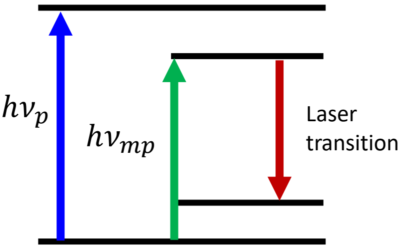
η_a = absorption efficiency

η_{pq} = power (energy) quantum efficiency

Optical pumping

Pumping rate

$$\left(\frac{dN_2}{dt}\right)_p = R_p = W_p N_g$$



Pumping efficiency

$$\boxed{\eta_p = \eta_r \eta_t \eta_a \eta_{pq}}$$

η_r = radiative efficiency

η_t = transfer efficiency

η_a = absorption efficiency

η_{pq} = power (energy) quantum efficiency

Pumping rate

$$\boxed{R_p = \eta_p \left(\frac{P_p}{Alh\nu_{mp}}\right)}$$

Optical pumping

$$\boxed{\eta_p = \eta_r \eta_t \eta_a \eta_{pq}}$$

Pumping efficiency

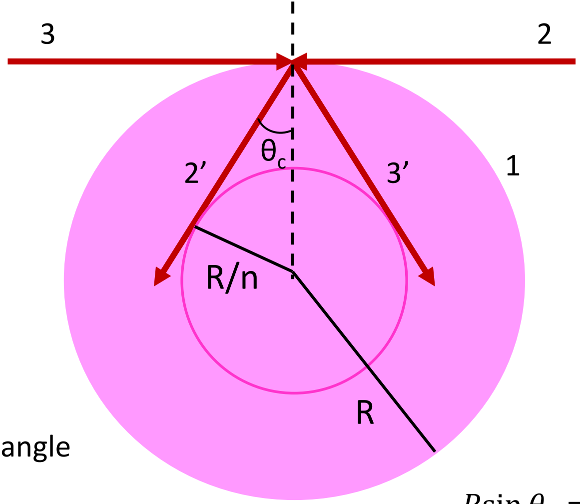
Gain medium	η_r (%)	η_t (%)	η_a (%)	η_{pq} (%)	η_p (%)
Ruby	27	78	31	46	3.0
Nd:YAG	43	82	17	59	3.5
Nd:glass	43	82	28	59	5.8

Pumping rate

$$\left(\frac{dN_2}{dt}\right)_p = R_p = W_p N_g$$

$$\boxed{R_p = \eta_p \left(\frac{P_p}{Alh\nu_{mp}}\right)}$$

Light distribution

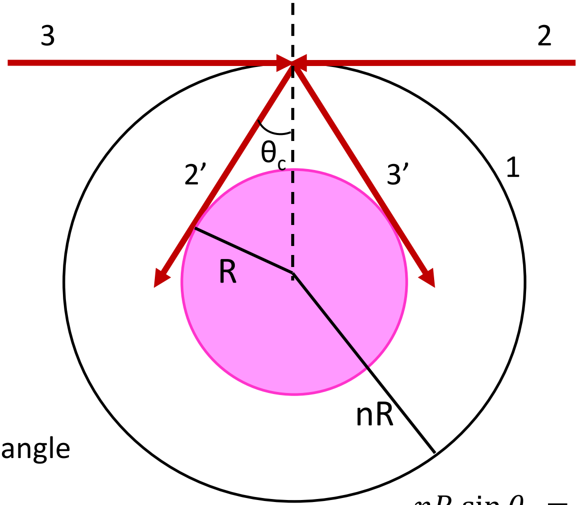


θ_c = critical angle

$$\sin\theta_c = \frac{1}{n}$$

$$R\sin\theta_c = R' = \frac{R}{n}$$

Cladding



θ_c = critical angle

$$\sin\theta_c = \frac{1}{n}$$

$$nR\sin\theta_c = R' = \frac{nR}{n} = R$$

with coherent sources: **Laser pumping**

- **longitudinal**: the pumping laser is aligned with optical cavity of the laser to pump.

absorption coefficient of the laser to pump

Pumping rate $$R_p = \frac{\alpha I_P(r,z)}{h\nu_p}$$

Intensity of the pump laser

Photon energy of the pump laser

- **transverse**: the pumping laser is aligned perpendicularly to the optical cavity of the laser to pump.

Incident pump power

Electrical power of the pump laser

$$\int_a h\nu_p\, R_p\, dV = \eta_a P_{Pi} \qquad P_{Pi} = \eta_r \eta_t P_P$$

absorption efficiency

radiative efficiency

transfer efficiency

Electrical pumping:

- **longitudinal**: the electrical discharge is produced longitudinally. It provides a more uniform pumping but requires higher applied voltages.

- **transverse**: the electrical discharge is produced perpendicularly with respect to the axis of the optical cavity.

Electrical power

Pumping rate $$\langle R_p \rangle = \eta_p \left(\frac{P}{V h \nu_{mp}} \right)$$

Average over the discharge volume

Laser modes

Modes of an optical resonator (**laser modes**): stationary configurations of the electromagnetic field which obey Maxwell's equations within the cavity with boundary conditions given by the presence of the mirrors.

They can be both **longitudinal** and **transverse**.

Longitudinal modes

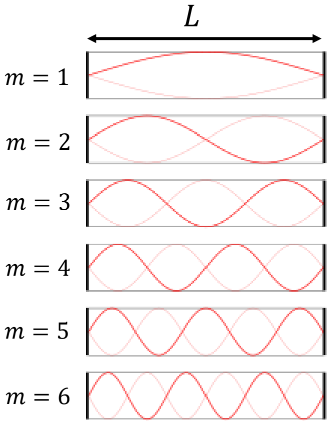
Fabry-Perot cavity

$$L = m\frac{\lambda}{2} \qquad \nu = \frac{c}{\lambda}$$

$$\nu = m\frac{c}{2L}$$

$$\boxed{\Delta\nu = \frac{c}{2L}}$$

Frequency difference between two adjoining modes



Laser modes

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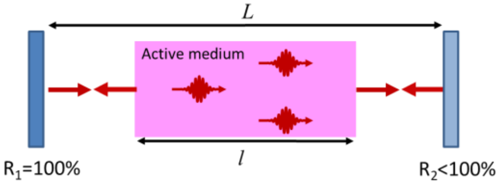
Longitudinal modes

Fabry-Perot cavity



$$L_e = m\frac{\lambda}{2} \qquad \nu = \frac{c}{\lambda}$$

$$\nu = m\frac{c}{2L_e}$$

$$L_e = (L - l) + nl = L + (n-1)l$$

Effective length of the cavity

$$\boxed{\Delta\nu = \frac{c}{2L_e}}$$

Frequency difference between two adjoining modes

Laser modes

Modes of an optical resonator (**laser modes**): stationary configurations of the electromagnetic field which obey Maxwell's equations within the cavity with boundary conditions given by the presence of the mirrors.

They can be both **longitudinal** and **transverse**

Longitudinal modes

Ring resonators

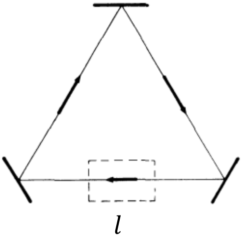
$$L_P = m\,\lambda \qquad \nu = \frac{c}{\lambda}$$

$$\nu = m\frac{c}{L_P}$$

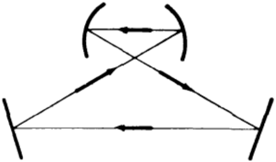
$$\boxed{\Delta\nu = \frac{c}{L_P}}$$

Frequency difference between two adjoining modes

3-mirrors



4-mirrors



$$L_P = L + (n-1)l$$

Effective perimeter of the cavity

Laser modes

Modes of an optical resonator (**laser modes**): stationary configurations of the electromagnetic field which obey Maxwell's equations within the cavity with boundary conditions given by the presence of the mirrors.

They can be both **longitudinal** and **transverse**

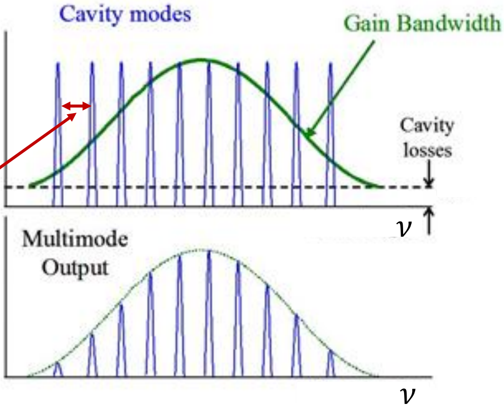
Longitudinal modes

Fabry-Perot cavity

$$L_e = m\frac{\lambda}{2} \qquad \nu = \frac{c}{\lambda}$$

$$\nu = m\frac{c}{2L_e}$$

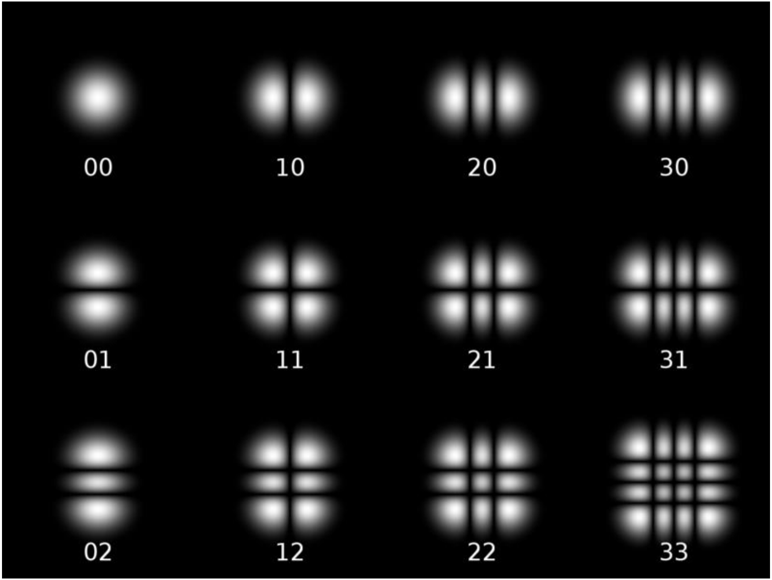
$$\boxed{\Delta\nu = \frac{c}{2L_e}}$$



Transverse modes (TEM_{mn})

Hermite-Gaussian

Brewster's windows in cavity



Gaussian modes (TEM_{mn})

Hermite-Gaussian

$$E_{mn}(x,y,z) = E_0 \frac{w_0}{w(z)} H_m\left(\frac{\sqrt{2}x}{w}\right) H_n\left(\frac{\sqrt{2}y}{w}\right) \times$$

$$\times \exp\left[-\frac{(x^2+y^2)}{w^2(z)} - ik\frac{(x^2+y^2)}{2R(z)} - ikz + i(m+n+1)\phi(z)\right]$$

$$H_0(u) = 1$$

$$H_1(u) = 2u$$

$$H_2(u) = 2(2u^2-1)$$

$$\dots$$

$$H_m(u) = (-1)^m e^{u^2} \frac{d^m\left(e^{-u^2}\right)}{du^m}$$

Hermite’s polynomials

Gaussian modes (TEM_{mn})

$$w^2(z) = w_0^2\left[1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2\right] = w_0^2\left[1+\left(\frac{z}{z_0}\right)^2\right]$$

Beam spot radius

$$w_0 = w(z=0)$$

Beam waist

$$z_0 = \frac{\pi w_0^2}{\lambda}$$

Rayleigh range

$$R(z) = z\left[1+\left(\frac{z_0}{z}\right)^2\right]$$

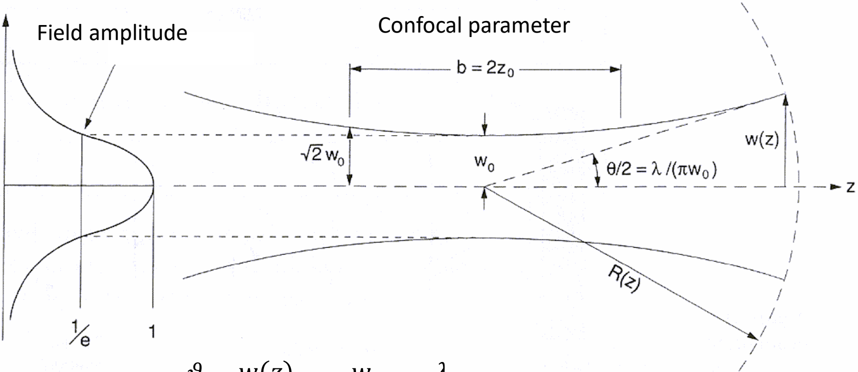
Wave-front curvature radius

$$\phi(z) = \tan^{-1}\left(\frac{z}{z_0}\right)$$

Phase factor

Gaussian mode TEM_{00}

$$E_{00}(x,y,z) = E_0 \frac{w_0}{w(z)} \exp\left[-\frac{(x^2+y^2)}{w^2(z)} - ik\frac{(x^2+y^2)}{2R(z)} - ikz + i\phi(z) \right]$$



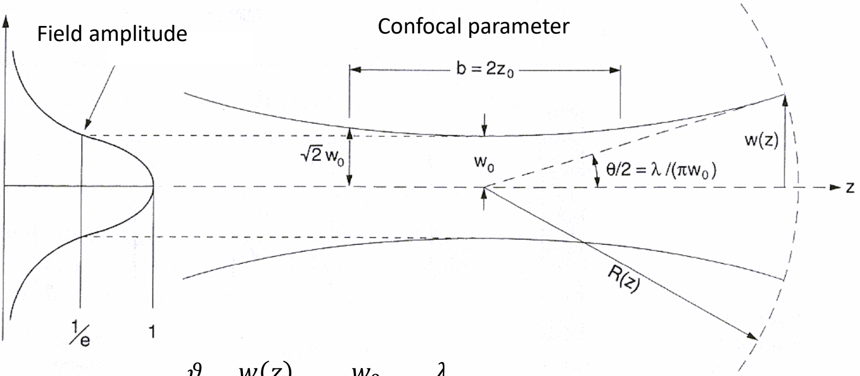
$$\frac{\vartheta}{2} \cong \frac{w(z)}{z} \xrightarrow[z \gg z_0]{} \frac{w_0}{z_0} = \frac{\lambda}{\pi w_0}$$

Far-field beam divergence

Gaussian mode TEM_{00}

Beam intensity

$$I_{00}(x,y,z)=\frac{1}{2}c\varepsilon_0|E_{00}(x,y,z)|^2=\frac{1}{2}c\varepsilon_0|E_0|^2\frac{w_0^2}{w(z)^2}e^{-2\frac{x^2+y^2}{w(z)^2}}=I_0\frac{1}{\left(1+\left(\frac{z}{z_0}\right)^2\right)}e^{-2\frac{x^2+y^2}{w(z)^2}}$$



$$\frac{\vartheta}{2}\cong\frac{w(z)}{z}\xrightarrow[z\gg z_0]{}\frac{w_0}{z_0}=\frac{\lambda}{\pi w_0}$$

Far-field beam divergence

M^2 - factor

For a perfectly Gaussian beam: $M^2 = 1$

$$w^2(z) = w_0^2\left[1+\left(M^2\frac{\lambda z}{\pi w_0^2}\right)^2\right] = w_0^2\left[1+\left(\frac{z}{z_M}\right)^2\right]$$

$$z_M = \frac{1}{M^2}\frac{\pi w_0^2}{\lambda} = \frac{z_0}{M^2}$$

$$\frac{\vartheta}{2} = \frac{w_0}{z_M} = \frac{M^2\lambda}{\pi w_0}$$