

Cours d'optique II

Physique
Master semestre I
2015-2016

-6- Laser
Preliminaires

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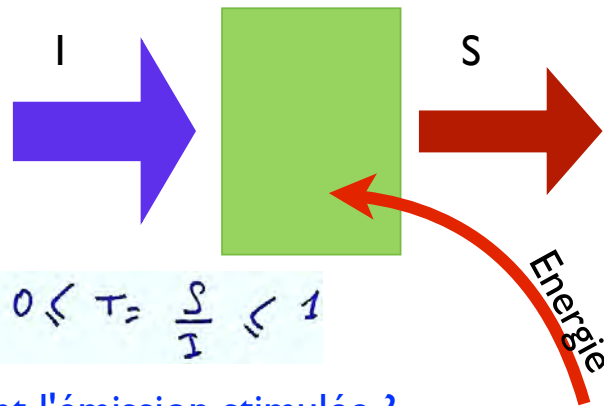
1

Bibliographie:

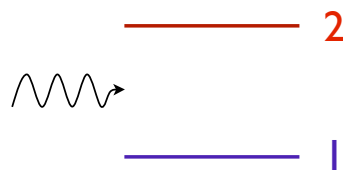
- * **Fundamentals of photonics** / B.E.A. Saleh et M.C. Tech, en anglais
- * **Optoélectronique** / E. Rosencher et B. Vinter, en français
- * **Lasers and electro-optics** / C.C. Davis, en anglais
- * **Principle of optics** / M. Born et E. Wolf, en anglais
- * **Lasers** / Milonni et Eberly, en anglais

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Amplificateur optique



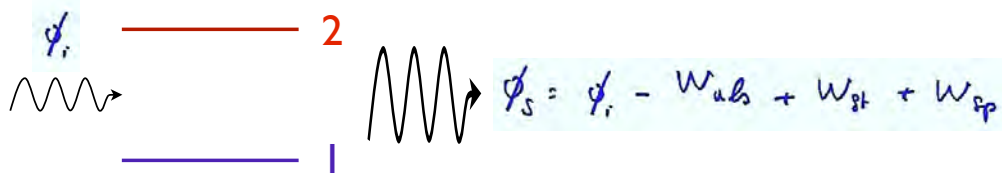
$T > I$ en utilisant l'émission stimulée ?



Systeme à deux niveaux

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Amplificateur optique



Absorption

$$W_{abs} = N_1 \phi_i \sigma(\nu)$$

Emission spontanée

$$W_{sp} = \frac{N_2}{\tau_{sp}}$$

Emission stimulée

$$W_{st} = N_2 \phi_i \sigma(\nu)$$

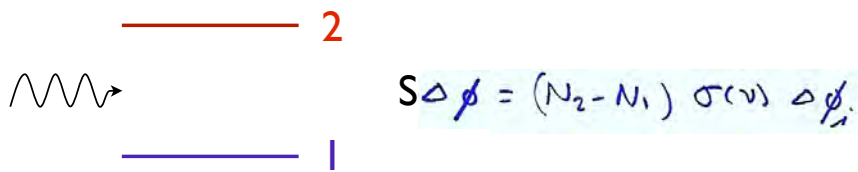
$$S \Delta \phi_s = S \Delta \phi_i - \Delta W_{abs} + \Delta W_{st}$$

$$S \Delta \phi = S \Delta \phi_s - S \Delta \phi_i = N_2 \Delta \phi_i \sigma(\nu) - N_1 \Delta \phi_i \sigma(\nu)$$

$$= (N_2 - N_1) \sigma(\nu) \Delta \phi_i$$

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Amplificateur optique



$$N_2 < N_1 \quad \Delta\phi < 0$$

Absorption

$$N_2 = N_1 \quad \Delta\phi = 0$$

Transparence

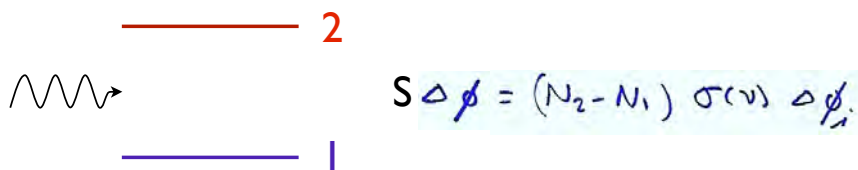
$$N_2 > N_1 \quad \Delta\phi > 0$$

Amplification

$$N_2 > N_1 \quad \text{Inversion de population}$$

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Amplificateur optique



$$N_1 + N_2 = N_a$$

Nombre total d'atomes

$$S\Delta\phi_{\text{abs}}^{\text{max}} = -N_a \sigma(\nu) \Delta\phi_i$$

$$S\Delta\phi_{\text{gain}}^{\text{max}} = N_a \sigma(\nu) \Delta\phi_i$$

$$\Delta\phi_{\text{gain}}^{\text{max}} = -\Delta\phi_{\text{abs}}^{\text{max}}$$

L'amplitude maximum du gain est égale aux pertes maximum (à $\Phi_i \rightarrow 0$)

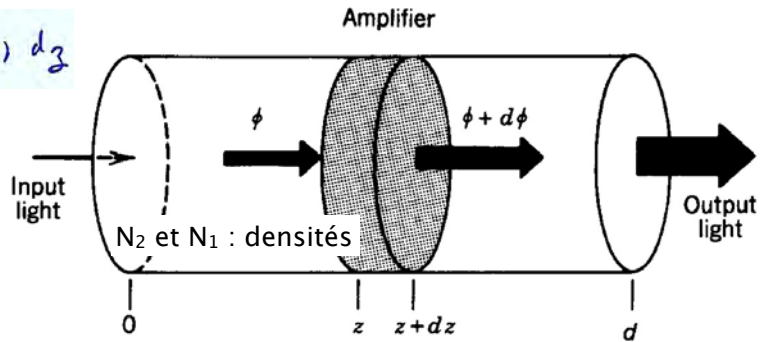
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Amplificateur optique

$$d\phi = (N_2 - N_1) \sigma(\nu) \phi_i(z) dz$$

$$\phi(z) = \phi_0 e^{(N_2 - N_1) \sigma(\nu) z}$$

$$= \phi_0 e^{\gamma z}$$



$$G = e^{\gamma d}$$

$$\gamma = (N_2 - N_1) \sigma(\nu)$$

$$\sigma(\nu) = S g(\nu)$$

$$S = \frac{\lambda^2}{8\pi c_{sp}}$$

$$= (N_2 - N_1) \frac{\lambda^2}{8\pi c_{sp}} g(\nu)$$

$$\gamma(\nu) = (N_2 - N_1) \frac{\lambda^2}{8\pi c_{sp}} g(\nu)$$

Gain du milieu amplificateur [L]⁻¹

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Amplificateur optique

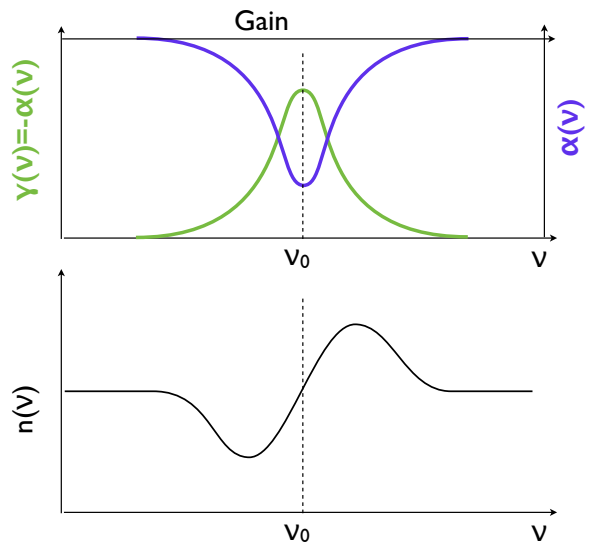
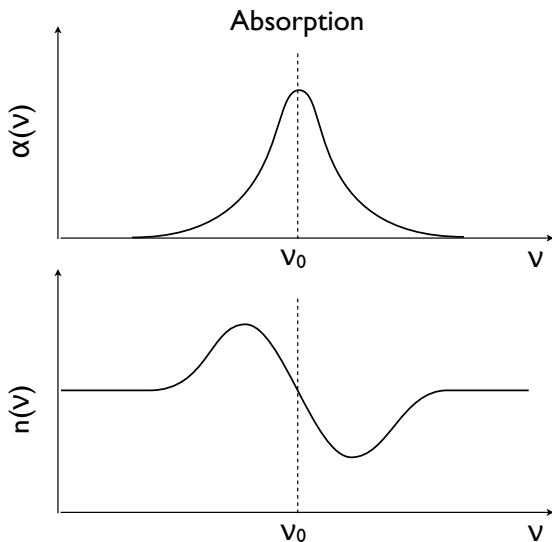
$$\gamma(\nu) = (N_2 - N_1) \frac{\lambda^2}{8\pi c_{sp}} g(\nu)$$

$$\tilde{n}(\nu) = n(\nu) + i k(\nu)$$

$$k(\nu) = - \frac{\gamma(\nu) d}{4\pi}$$

$$k > 0 \quad e^{i(k\vec{r} - \omega t)}$$

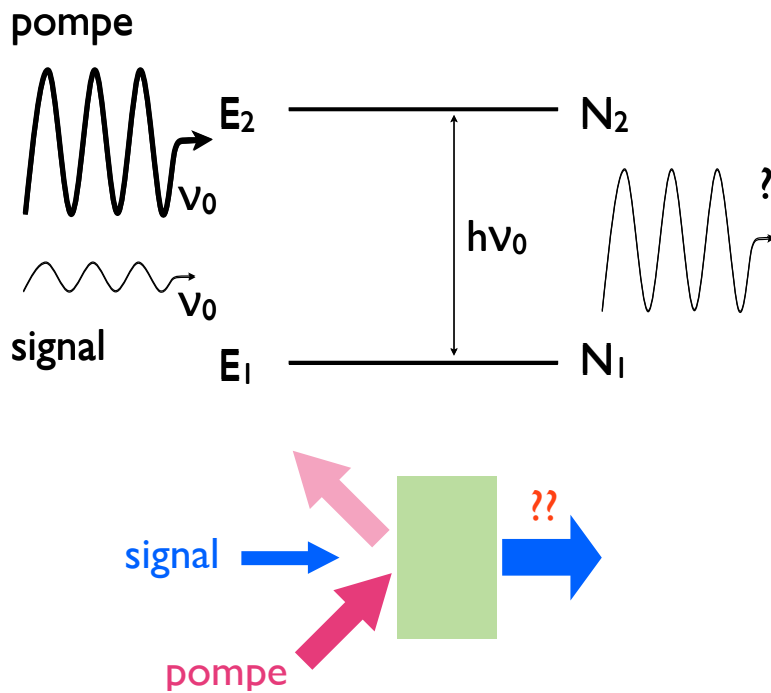
$$k < 0 \quad e^{i(\omega t - k\vec{r})}$$



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Amplificateur optique

Système à deux niveaux



Amplificateur optique

Système à deux niveaux

Absorption

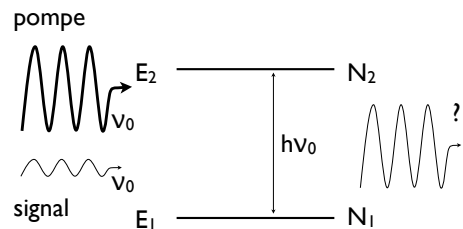
$$\frac{\bar{n} N_1}{\sigma_{sp}}$$

Emission spontanée

$$\frac{N_2}{\sigma_{sp}}$$

Emission stimulée

$$\frac{\bar{n} N_2}{\sigma_{sp}}$$



$$\frac{dN_1}{dt} = -\frac{dN_2}{dt} = \frac{(1+\bar{n})N_2}{\sigma_{sp}} - \frac{\bar{n}N_1}{\sigma_{sp}} = 0$$

$$N_2 = \frac{\bar{n}}{1+\bar{n}} N_1$$

$$N = N_2 + N_1$$



$$N_1 = \frac{1+\bar{n}}{1+2\bar{n}} N$$

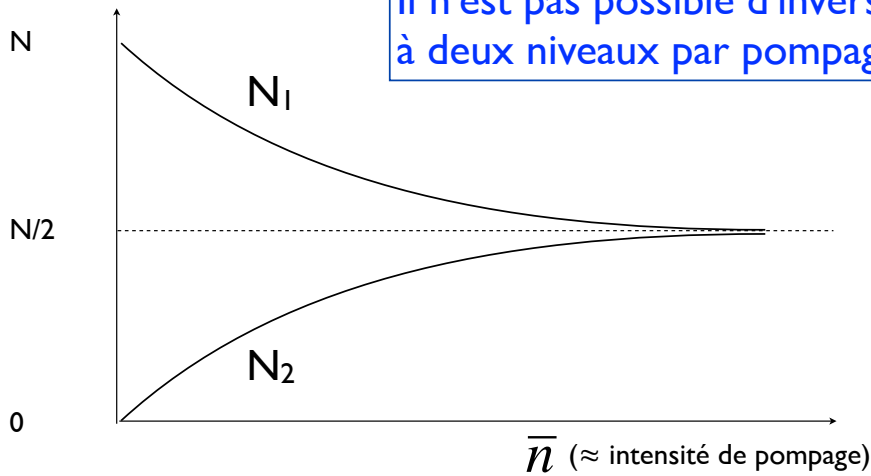
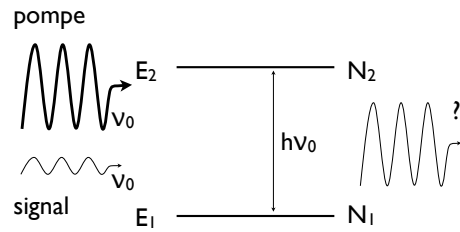
$$N_2 = \frac{\bar{n}}{1+2\bar{n}} N$$

Amplificateur optique

Système à deux niveaux

$$N_1 = \frac{1 + \bar{n}}{1 + 2\bar{n}} N \quad N_2 = \frac{\bar{n}}{1 + 2\bar{n}} N$$

$$N_2 < N_1$$



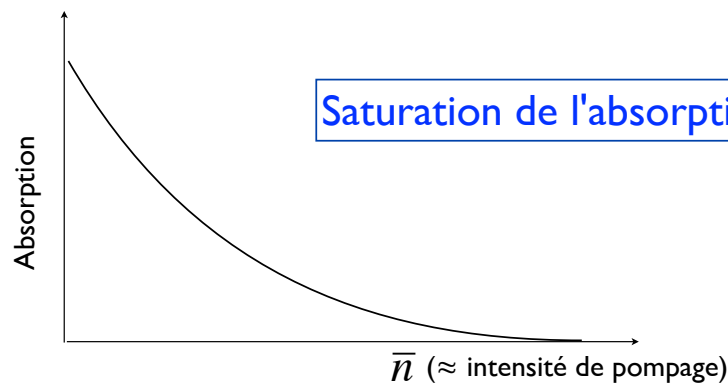
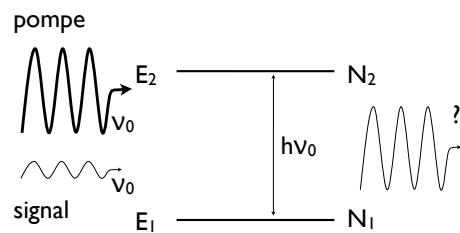
Il n'est pas possible d'inverser un système à deux niveaux par pompage optique

Amplificateur optique

Système à deux niveaux

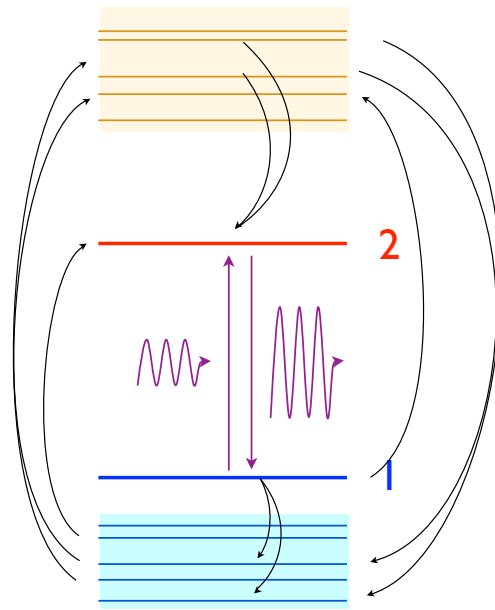
$$N_1 = \frac{1 + \bar{n}}{1 + 2\bar{n}} N \quad N_2 = \frac{\bar{n}}{1 + 2\bar{n}} N$$

Absorption $\propto \frac{N_1 - N_2}{\sigma_f} = \frac{1}{1 + 2\bar{n}} N$



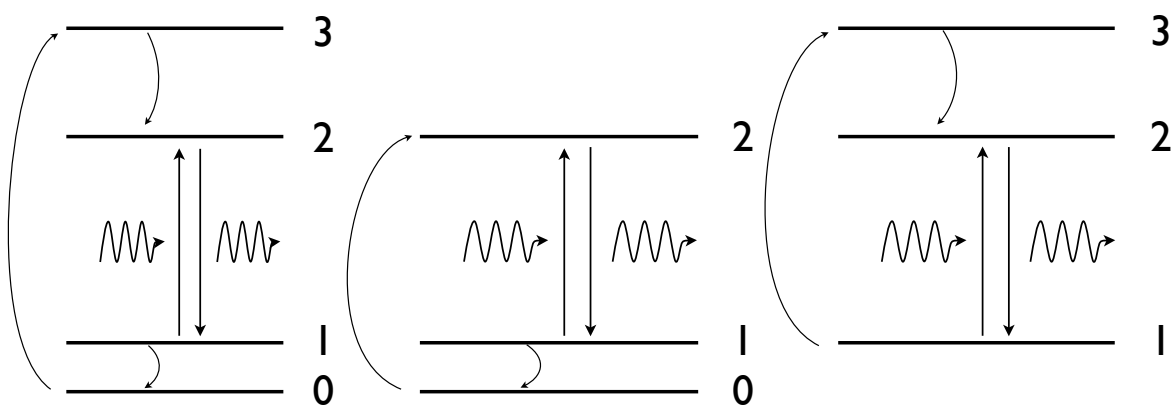
Saturation de l'absorption

Amplificateur optique



Systeme à deux niveaux en interaction avec d'autres

Amplificateur optique



Systeme à quatre niveaux

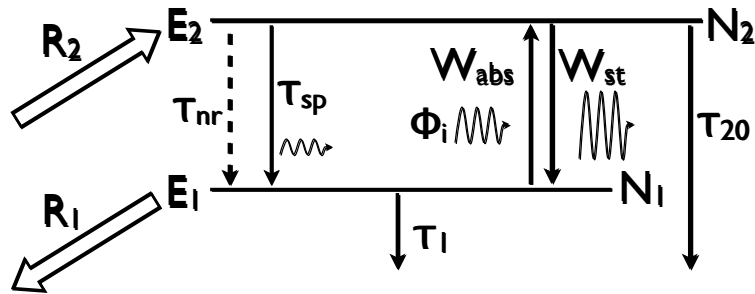
Cas I

Cas II

Systemes à trois niveaux

Amplificateur optique

Système à deux niveaux en interaction avec d'autres



Pompage R_1, R_2

Emission spontanée

$$\frac{N_2}{\tau_{sp}}$$

Recombinaison non radiatives

$$\frac{N_2}{\tau_{nr}}$$

Désexcitation de 2

$$\frac{N_2}{\tau_{20}}$$

Désexcitation de 1

$$\frac{N_1}{\tau_1}$$

Absorption

$$N_1 \omega_i$$

$$\omega_i = \sigma(\nu) \phi_i$$

Emission stimulée

$$N_2 \omega_i$$

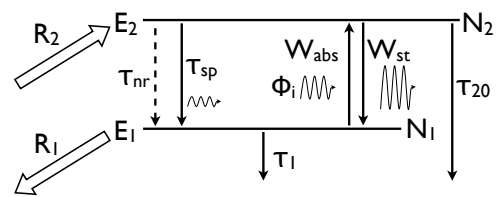
Amplificateur optique

Système à deux niveaux en interaction avec d'autres

$2 \rightarrow 1$ $\frac{1}{\tau_{21}} = \frac{1}{\tau_{nr}} + \frac{1}{\tau_{sp}}$

Temps de vie de 2 $\frac{1}{\tau_2} = \frac{1}{\tau_{20}} + \frac{1}{\tau_{21}}$

Sans flux incident



$$0 = \frac{dN_2}{dt} = R_2 - \frac{N_2}{\tau_2}$$

$$N_2^0 = R_2 \tau_2$$

$$0 = \frac{dN_1}{dt} = -R_1 - \frac{N_1}{\tau_1} + \frac{N_2}{\tau_{21}}$$

$$N_1^0 = \tau_1 \left(\frac{N_2^0}{\tau_{21}} - R_1 \right)$$

$$= \frac{\tau_1 \tau_2}{\tau_{21}} R_2 - \tau_1 R_1$$

Amplificateur optique

Système à deux niveaux en interaction avec d'autres

$$N_2^0 = R_2 \sigma_2 \quad N_1^0 = \frac{\sigma_1 \sigma_2}{\sigma_{21}} R_2 - \sigma_1 R_1$$

$$N^0 = N_2^0 - N_1^0 = \sigma_2 \left(1 - \frac{\sigma_1}{\sigma_{21}} \right) R_2 + \sigma_1 R_1$$

- $N^0 \nearrow$ avec R_1 même si $R_2 \rightarrow 0$
- $\tau_1 < \tau_{21}$: 1 se vide plus vite que 2
- τ_2 est grand :

$$N^0 = \sigma_2 \left(1 - \sigma_1 \left(\frac{1}{\sigma_1} - \frac{1}{\sigma_{20}} \right) \right) R_2 + \sigma_1 R_1$$

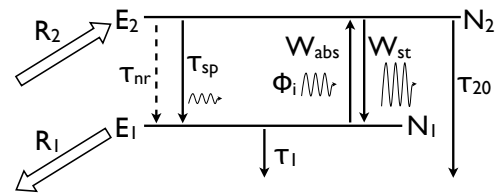
$$= \sigma_2 \left(1 + \frac{\sigma_1}{\sigma_{20}} \right) R_2 + \sigma_1 (R_1 - R_2)$$

Cas idéal :

$$\sigma_{nr} \rightarrow \infty \quad \sigma_{21} = \sigma_{sp}$$

$$\sigma_1 \ll \sigma_{21} \quad \sigma_2 = \sigma_{sp}$$

$$N^0 = \sigma_2 R_2 + \sigma_1 R_1$$



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Amplificateur optique

Système à deux niveaux en interaction avec d'autres

Avec flux incident

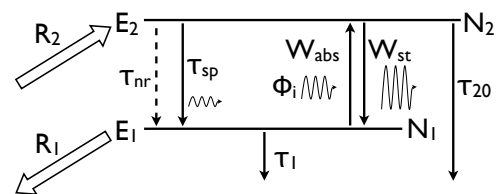
$$0 = \frac{dN_2}{dt} = R_2 - \frac{N_2}{\tau_2} - N_2 W_i + N_1 W_i$$

$$0 = \frac{dN_1}{dt} = -R_1 - \frac{N_1}{\tau_1} + \frac{N_2}{\tau_{21}} + N_2 W_i - N_1 W_i$$

$$\begin{cases} R_1 = - \left(\frac{1}{\tau_1} + W_i \right) N_1 + \left(\frac{1}{\tau_{21}} + W_i \right) N_2 \\ R_2 = - W_i N_1 + \left(\frac{1}{\tau_2} + W_i \right) N_2 \end{cases}$$

$$N_1 = \frac{1}{\frac{1}{\sigma_1 \sigma_2} + \left(\frac{1}{\sigma_1} + \frac{1}{\sigma_2} - \frac{1}{\sigma_{21}} \right) W_i} \left(\left(\frac{1}{\sigma_{21}} + W_i \right) R_2 - \left(\frac{1}{\sigma_2} + W_i \right) R_1 \right)$$

$$N_2 = \frac{1}{\frac{1}{\sigma_1 \sigma_2} + \left(\frac{1}{\sigma_1} + \frac{1}{\sigma_2} - \frac{1}{\sigma_{21}} \right) W_i} \left(\left(\frac{1}{\sigma_2} + W_i \right) R_2 - W_i R_1 \right)$$



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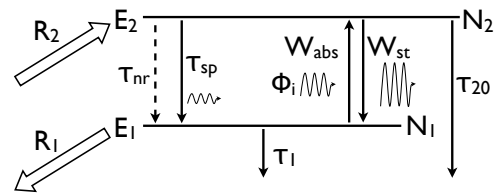
Amplificateur optique

Système à deux niveaux en interaction avec d'autres

Avec flux incident

$$N_1 = \frac{1}{\sigma_1 \sigma_2 + \left(\frac{1}{\sigma_1} + \frac{1}{\sigma_2} - \frac{1}{\sigma_{21}}\right) W_i} \left(\left(\frac{1}{\sigma_{21}} + W_i\right) R_2 - \left(\frac{1}{\sigma_2} + W_i\right) R_1 \right)$$

$$N_2 = \frac{1}{\sigma_1 \sigma_2 + \left(\frac{1}{\sigma_1} + \frac{1}{\sigma_2} - \frac{1}{\sigma_{21}}\right) W_i} \left(\left(\frac{1}{\sigma_2} + W_i\right) R_2 - W_i R_1 \right)$$

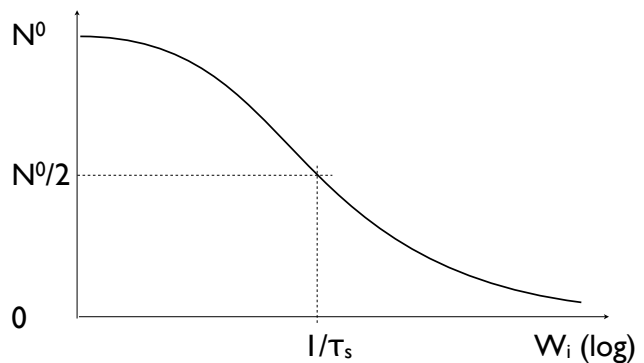


$$\Delta N = N_2 - N_1 = \frac{N^0}{1 + \sigma_s W_i}$$

$$\sigma_s = \sigma_2 + \sigma_1 \left(1 - \frac{\sigma_2}{\sigma_{21}}\right)$$

$$N^0 = \sigma_2 \left(1 - \frac{\sigma_1}{\sigma_{21}}\right) R_2 + \sigma_1 R_1$$

Saturation de l'inversion



Amplificateur optique

Système à deux niveaux en interaction avec d'autres

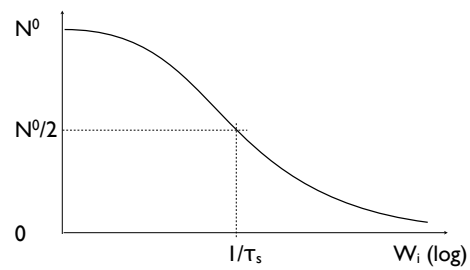
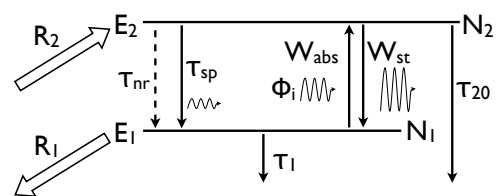
$$\Delta N = N_2 - N_1 = \frac{N^0}{1 + \sigma_s W_i}$$

En fonction du flux incident

$$W = \phi \sigma(\nu) = \phi S g(\nu) = \phi \frac{d^2}{8\pi \sigma_{sp}} g(\nu)$$

$$\Delta N = \frac{N^0}{1 + \sigma_s W_i} = \frac{N^0}{1 + \frac{d^2}{8\pi} \frac{\sigma_s}{\sigma_{sp}} g(\nu) \phi_i}$$

$$= \frac{N^0}{1 + \frac{\phi_i}{\phi_s}}$$



Saturation de l'inversion

$$\frac{1}{\phi_s} = \frac{d^2}{8\pi} \frac{\sigma_s}{\sigma_{sp}} g(\nu)$$

Amplificateur optique

Système à deux niveaux en interaction avec d'autres

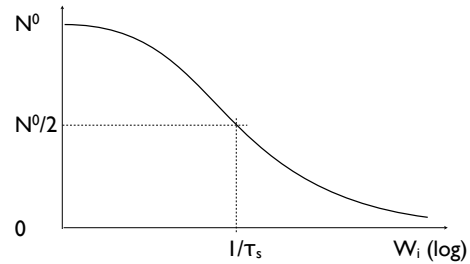
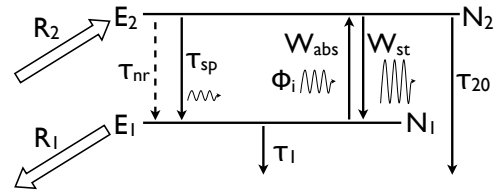
Saturation du gain

$$g(\nu) = \Delta N \frac{d^2}{8\pi \sigma_{sp}} g(\nu)$$

$$= \frac{g^0(\nu)}{1 + \frac{\phi_i}{\phi_s}}$$

Cas idéal :

$$\begin{aligned} \sigma_1 &\ll \sigma_{sp} & \ll \sigma_{20} & \ll \sigma_{nr} \\ \sigma_{21} &= \sigma_{sp} & \sigma_2 &= \sigma_{sp} & \sigma_s &= \sigma_{sp} \end{aligned}$$

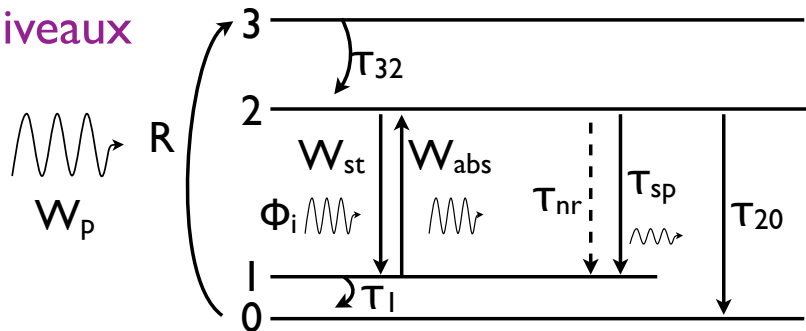


Amplificateur optique

Système à quatre niveaux

$$\sigma_{nr} \rightarrow \infty$$

$$\frac{1}{\sigma_2} = \frac{1}{\sigma_{sp}} + \frac{1}{\sigma_{20}}$$



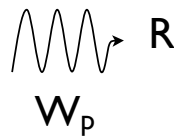
$$\begin{cases} 0 = \frac{dN_3}{dt} = R - \frac{N_3}{\sigma_{32}} \\ 0 = \frac{dN_2}{dt} = \frac{N_3}{\sigma_{32}} - \frac{N_2}{\sigma_2} - N_2 W_i + N_1 W_i \\ 0 = \frac{dN_1}{dt} = -\frac{N_1}{\sigma_1} + \frac{N_2}{\sigma_{21}} + N_2 W_i - N_1 W_i \\ 0 = -R + \frac{N_1}{\sigma_1} + \frac{N_2}{\sigma_{20}} \end{cases}$$



Amplificateur optique

Système à quatre niveaux

$$\Delta N = \frac{N^0}{1 + \tau_S \omega_i}$$



$$\tau_S = \tau_2 + \tau_1 \left(1 - \frac{\tau_2}{\tau_{21}}\right)$$

$$N^0 = \tau_2 \left(1 - \frac{\tau_1}{\tau_{21}}\right) R$$

Cas idéal :

$$\tau_1 \ll \tau_{sp} \ll \tau_{20} \ll \tau_{nr}$$

$$\tau_S = \tau_{sp} \quad \tau_{21} = \tau_{sp} \quad \tau_2 = \tau_{sp}$$

$$\Delta N = \frac{N^0}{1 + \tau_{sp} \omega_i}$$

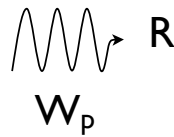
$$N^0 = \tau_{sp} R$$

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Amplificateur optique

$$\Delta N = \frac{N^0}{1 + \tau_{sp} \omega_i}$$

$$N^0 = \tau_{sp} R$$



$$0 \rightarrow 3 \quad N_0 \phi_p \sigma(\nu) = N_0 \omega_p$$

$$3 \rightarrow 0 \quad N_3 \omega_p$$

$$N_0 + N_1 + N_2 + N_3 = N_a$$

$$R = (N_0 - N_3) \omega_p$$

$$N_3, N_1 \ll N_a, N_0, N_2$$

$$\approx (N_a - N_2) \omega_p$$

$$\approx (N_a - \Delta N) \omega_p$$

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Amplificateur optique

$$\Delta N = \frac{N^0}{1 + \sigma_{sp} W_i}$$

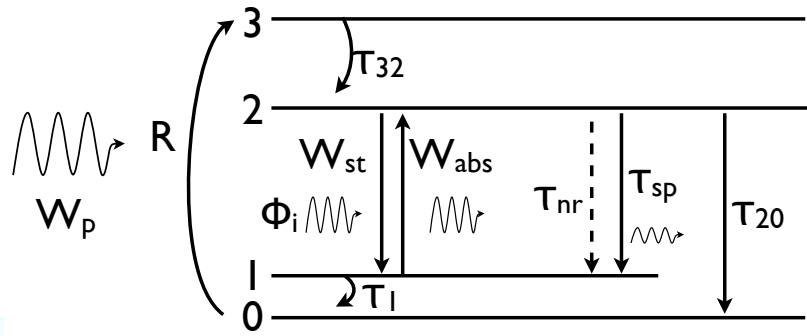
$$N^0 = \sigma_{sp} R$$

$$R \approx (N_a - \Delta N) W_p$$

$$\Delta N = \frac{(N_a - \Delta N) \sigma_{sp} W_p}{1 + \sigma_{sp} W_i}$$

$$\Delta N \left(1 + \frac{\sigma_{sp} W_p}{1 + \sigma_{sp} W_i} \right) = \frac{N_a \sigma_{sp} W_p}{1 + \sigma_s W_i} \quad \Delta N = \frac{N_a \sigma_{sp} W_p}{1 + \sigma_{sp} W_p + \sigma_{sp} W_i}$$

$$\Delta N = \frac{\tilde{N}_0}{1 + \sigma_s W_i} \quad \sigma_s = \frac{\sigma_{sp}}{1 + \sigma_{sp} W_p} \quad \tilde{N}_0 = \frac{N_a \sigma_{sp} W_p}{1 + \sigma_{sp} W_p} \quad \text{Saturation du pompage}$$



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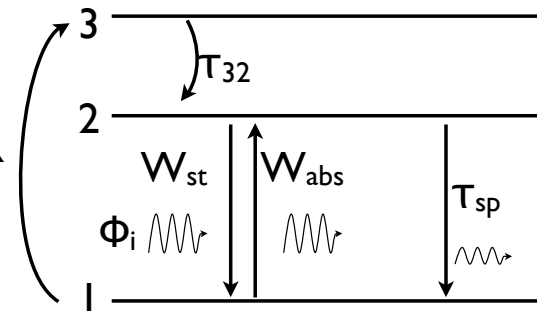
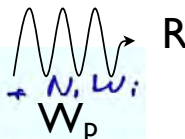
Amplificateur optique

Système à trois niveaux

$$0 = R - \frac{N_3}{\tau_{32}}$$

$$0 = \frac{N_3}{\tau_{32}} - \frac{N_2}{\tau_{sp}} - N_2 W_i + N_1 W_i$$

$$0 = -R + \frac{N_2}{\tau_{sp}} + N_2 W_i - N_1 W_i$$



$$N_a = N_1 + N_2 + N_3$$



$$\Delta N = \frac{2R\sigma_{sp} - N_a}{1 + 2\sigma_{sp} W_i} = \frac{N'^0}{1 + \sigma_s W_i}$$

Système à trois niveaux

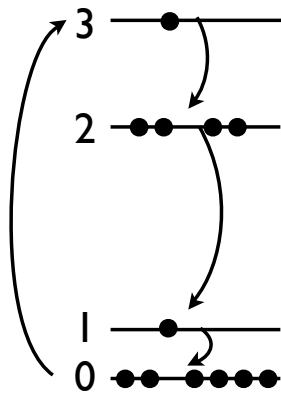
$$N'^0 = 2R\sigma_{sp} - N_a \quad \sigma_s = 2\sigma_{sp}$$

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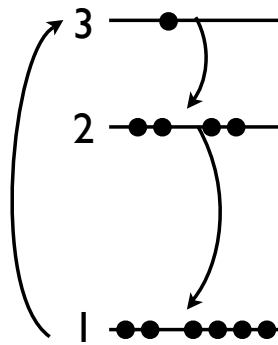
Amplificateur optique

$$N^0 = \tau_{sp} R$$

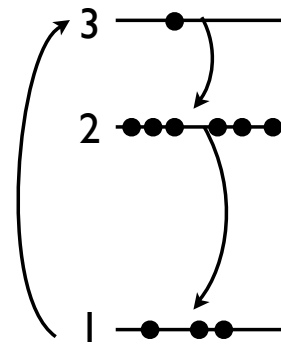
$$N^0 = 2R\tau_{sp} - N_a$$



4 niveaux



faible pompage



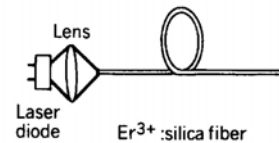
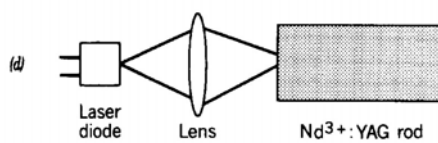
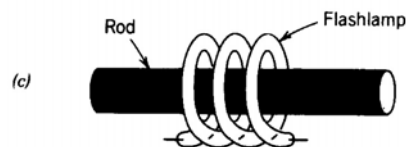
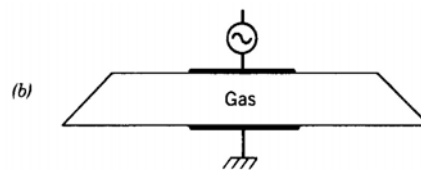
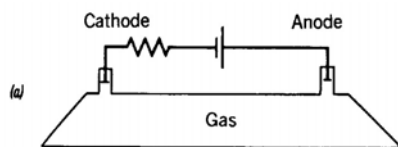
fort pompage

3 niveaux

Amplificateur optique

Exemples

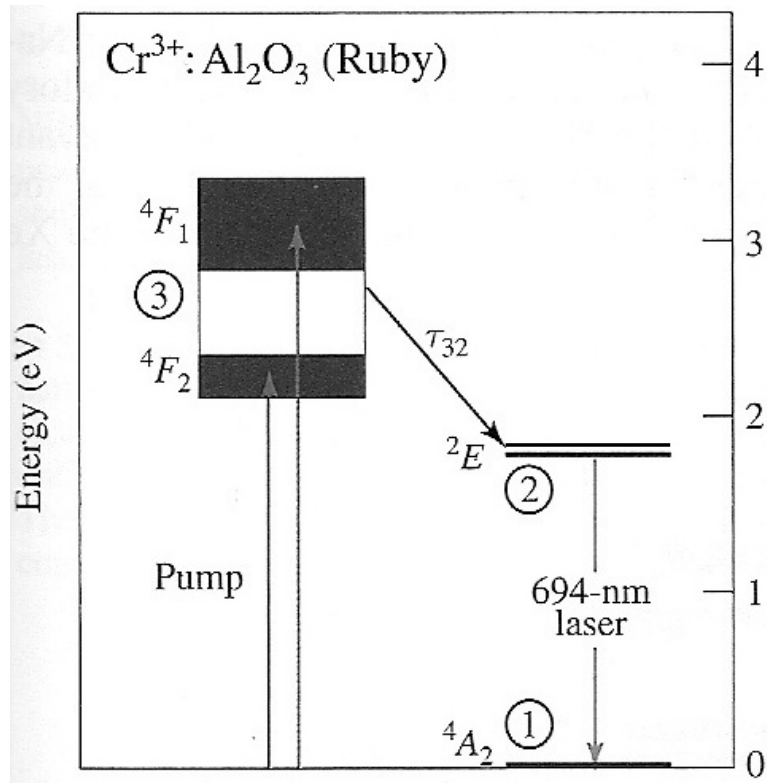
Pompage



Amplificateur optique

Exemples

Rubis

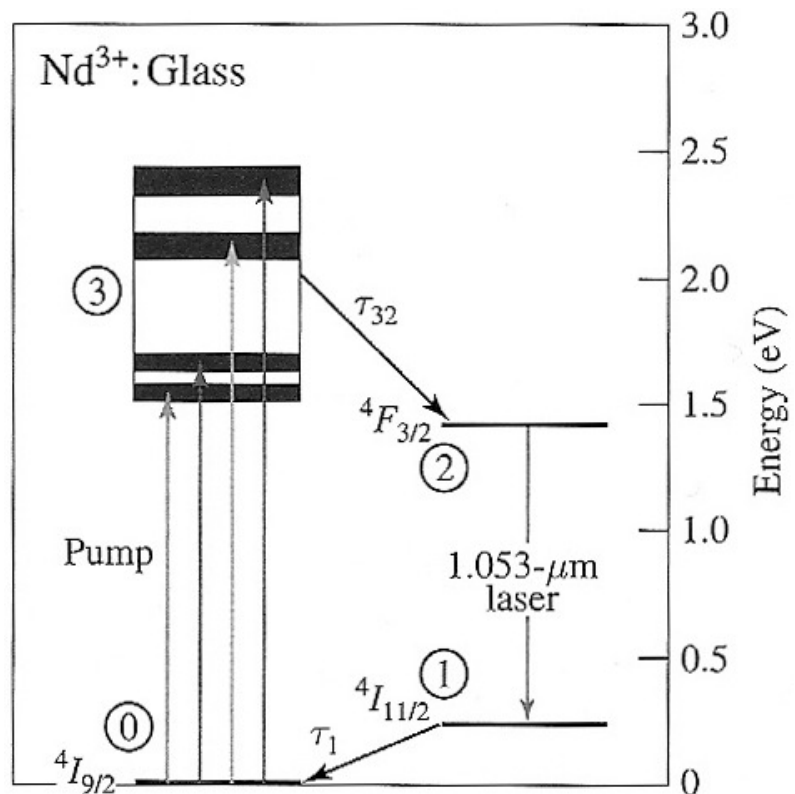


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Amplificateur optique

Exemples

Verre dopé néodyme

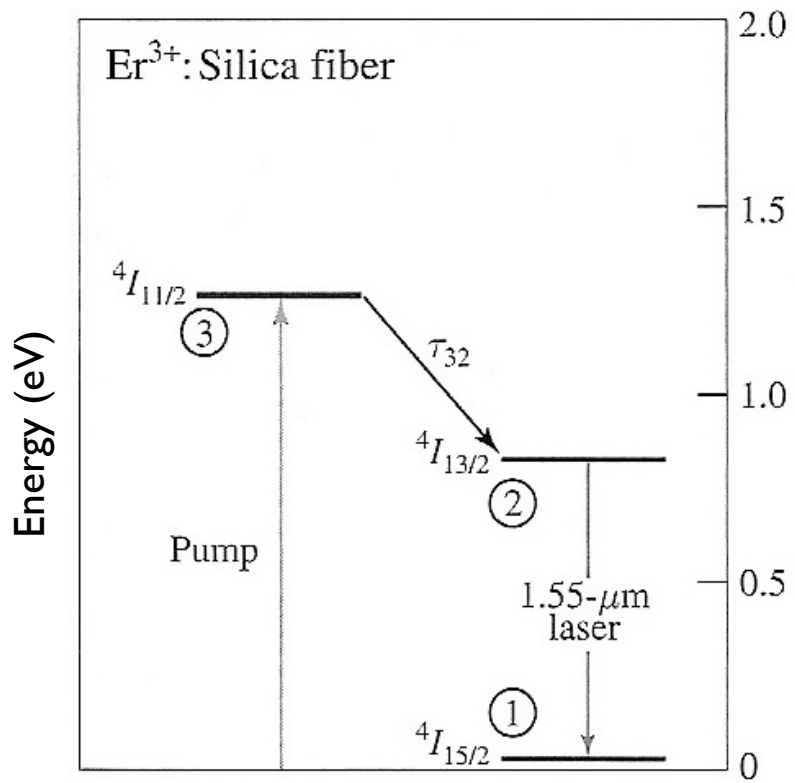


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Amplificateur optique

Exemples

Verre dopé erbium

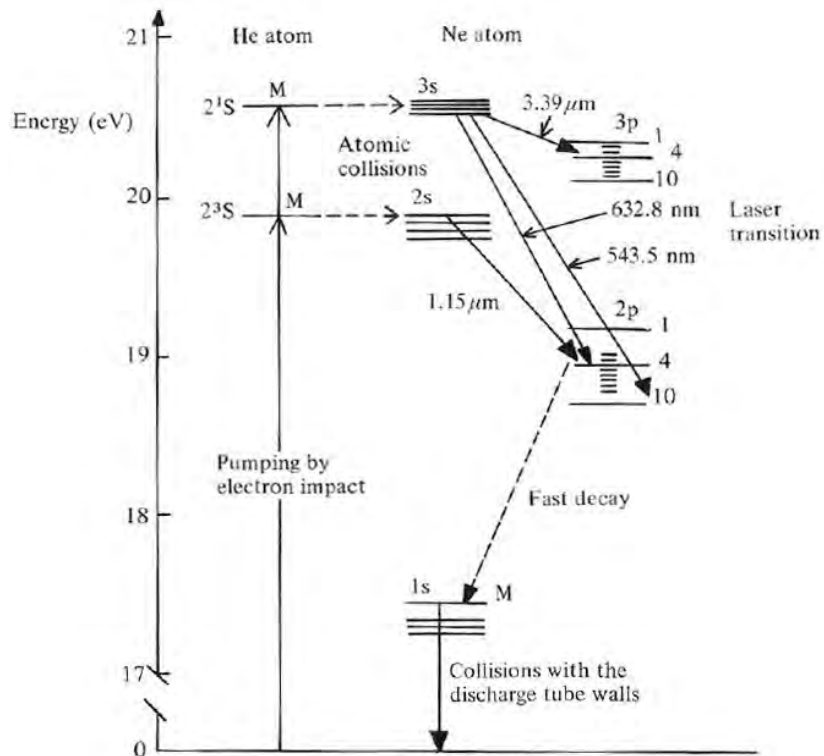


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Amplificateur optique

Exemples

Hélium-Néon

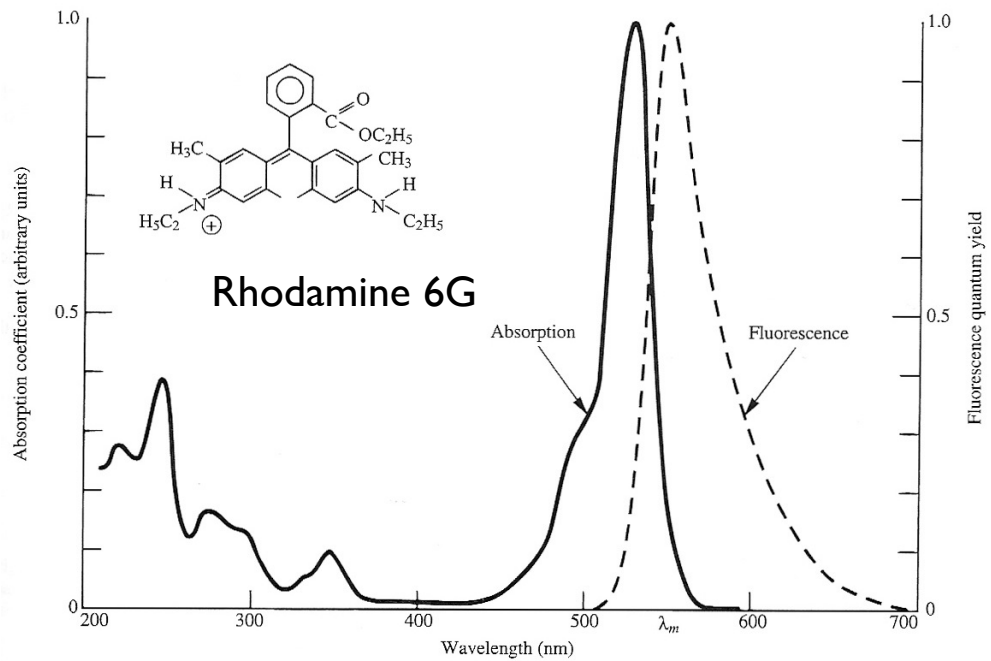


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Amplificateur optique

Exemples

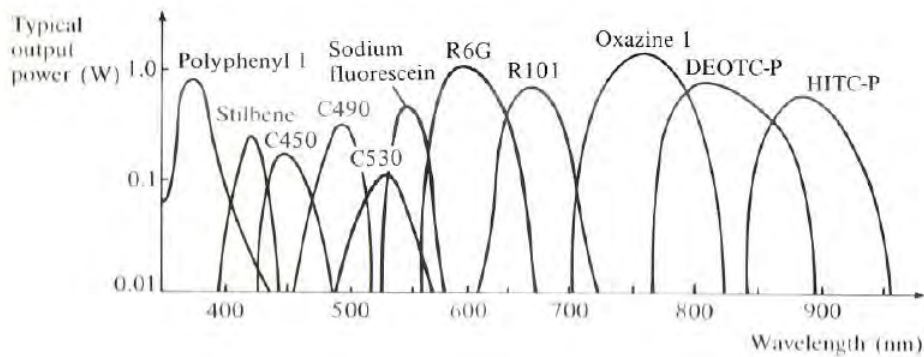
Colorant



Amplificateur optique

Exemples

Colorant



Amplificateur optique

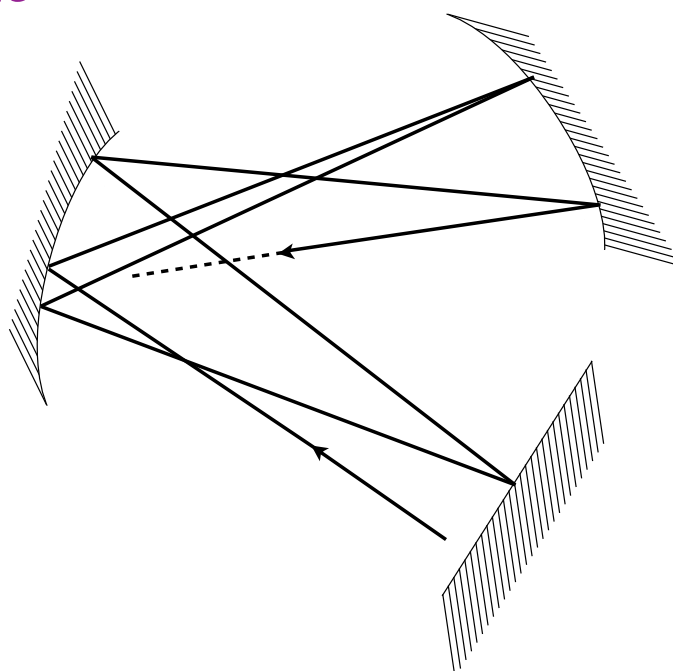
Exemples

Laser Medium	Transition Wavelength ^a λ_o (nm)	Transition Cross Section σ_0 (cm ²)	Spontaneous Lifetime t_{sp}	Transition Linewidth ^b $\Delta\nu$		Refractive Index n
C ⁵⁺	18.2	5×10^{-16}	12 ps	1 THz	I	≈ 1
ArF Excimer	193	3×10^{-16}	10 ns	10 THz	I	≈ 1
Ar ⁺	515	3×10^{-12}	10 ns	3.5 GHz	I	≈ 1
Rhodamine-6G dye	560–640	2×10^{-16}	5 ns	40 THz	H/I	1.40
He-Ne	633	3×10^{-13}	150 ns	1.5 GHz	I	≈ 1
Cr ³⁺ :Al ₂ O ₃	694	2×10^{-20}	3 ms	330 GHz	H	1.76
Cr ³⁺ :BeAl ₂ O ₄	700–820	1×10^{-20}	260 μ s	25 THz	H	1.74
Ti ³⁺ :Al ₂ O ₃	700–1050	3×10^{-19}	3.9 μ s	100 THz	H	1.76
Yb ³⁺ :YAG	1030	2×10^{-20}	1 ms	1 THz	H	1.82
Nd ³⁺ :Glass (phosphate)	1053	4×10^{-20}	370 μ s	7 THz	I	1.50
Nd ³⁺ :YAG	1064	3×10^{-19}	230 μ s	150 GHz	H	1.82
Nd ³⁺ :YVO ₄	1064	8×10^{-19}	100 μ s	210 GHz	H	2.0
InGaAsP ^c	1300–1600	2×10^{-16}	2.5 ns	10 THz	H	3.54
Er ³⁺ :Silica fiber	1550	6×10^{-21}	10 ms	5 THz	H/I	1.46
CO ₂	10 600	3×10^{-18}	3 s	60 MHz	I	≈ 1

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Résonateur optique

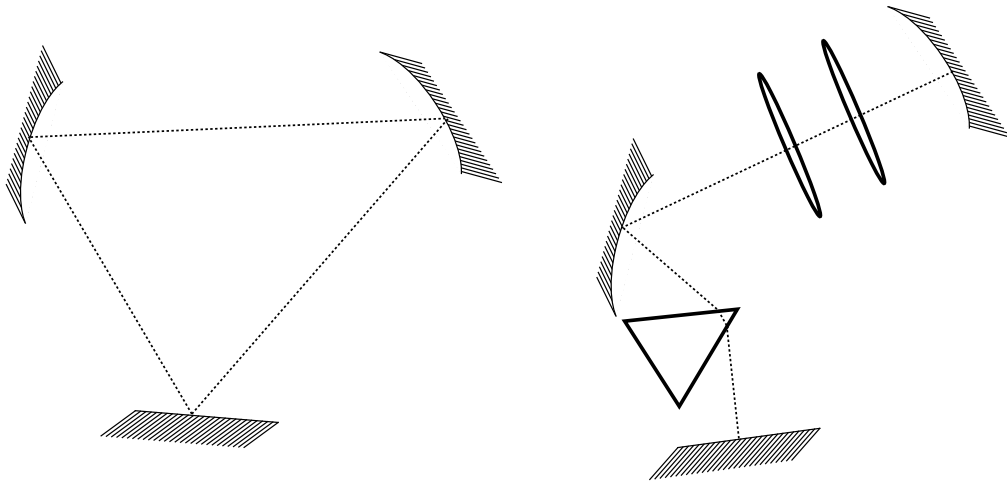
Géométrie



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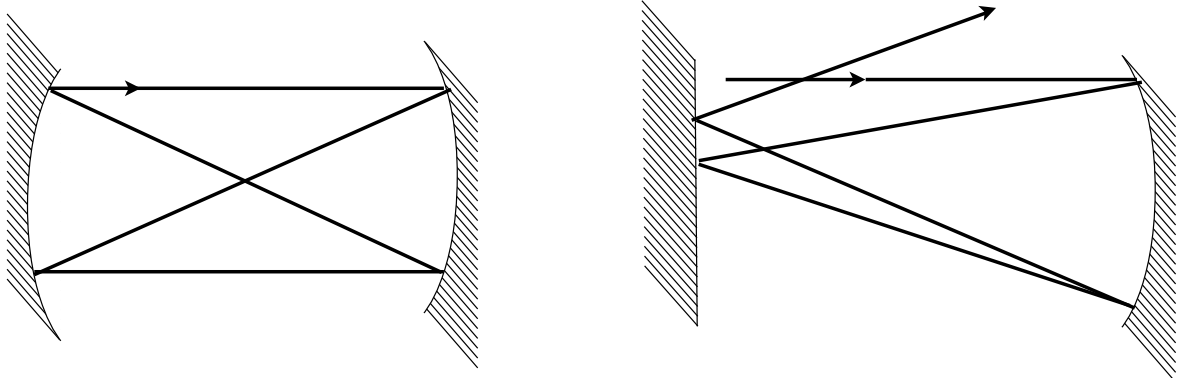
Résonateur optique

Géométrie



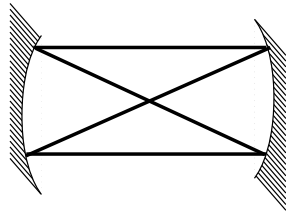
Résonateur optique

Stabilité

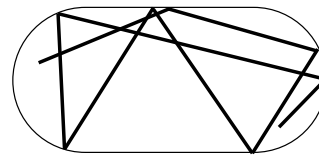


Résonateur optique

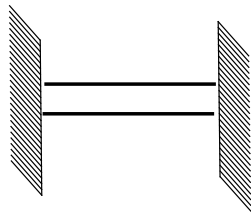
Stabilité



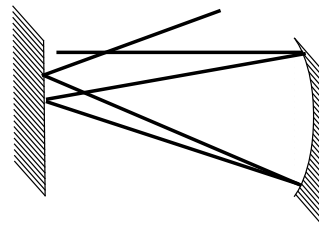
stable



chaotique



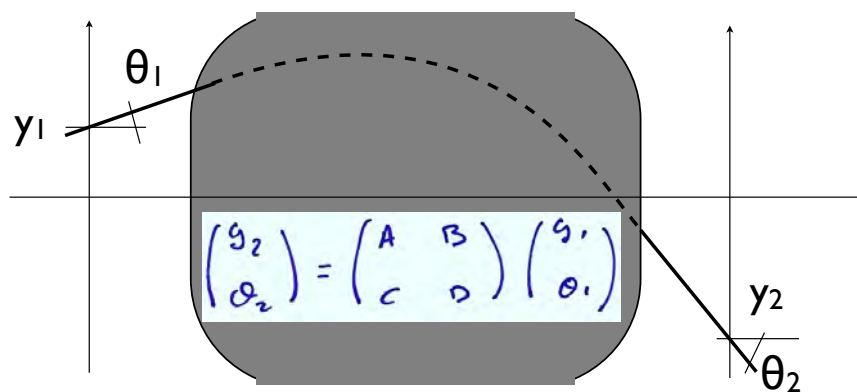
conditionnellement stable



instable

Résonateur optique

Stabilité



$$\begin{pmatrix} y_2 \\ \theta_2 \end{pmatrix} = M_m \dots M_2 M_1 \begin{pmatrix} y_1 \\ \theta_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} y_1 \\ \theta_1 \end{pmatrix}$$

$$\begin{pmatrix} y_N \\ \theta_N \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^N \begin{pmatrix} y_1 \\ \theta_1 \end{pmatrix} = M^N \begin{pmatrix} y_1 \\ \theta_1 \end{pmatrix}$$

Résonateur optique

Stabilité

$$\begin{pmatrix} q_N \\ \theta_N \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^N \begin{pmatrix} q_1 \\ \theta_1 \end{pmatrix} = M^N \begin{pmatrix} q_1 \\ \theta_1 \end{pmatrix}$$

$$\det M = \det M_1 \times \dots \times \det M_1 = 1$$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix}^N = \frac{1}{\sin z} \begin{pmatrix} A \sin Nz - \sin(N-1)z & B \sin Nz \\ C \sin Nz & D \sin Nz - \sin(N-1)z \end{pmatrix} \quad \cos z = \frac{A+D}{2}$$

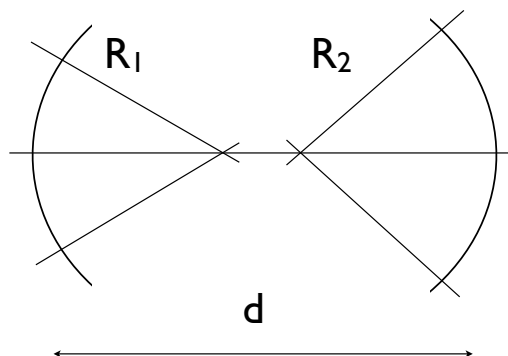
$$\sin z = \frac{B}{2} \quad \cos z = \frac{D}{2}$$

$\left \frac{A+D}{2} \right < 1$	Stable
$\left \frac{A+D}{2} \right = 1$	Conditionnellement stable
$\left \frac{A+D}{2} \right > 1$	Instable

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Résonateur optique

Miroirs sphériques et modes Gaussiens



$R < 0$ concave

$R > 0$ convexe

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 2/R_1 & 1 \end{pmatrix} \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 2/R_2 & 1 \end{pmatrix} \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$$

$$0 \leq \left(1 + \frac{d}{R_1}\right) \left(1 + \frac{d}{R_2}\right) \leq 1 \quad \text{Condition de stabilité d'un résonateur sphérique}$$

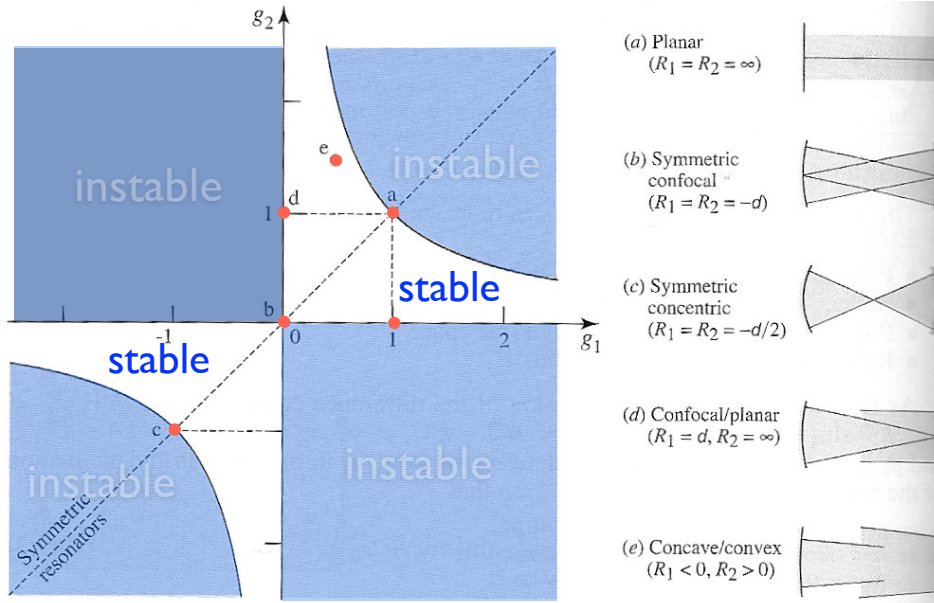
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Résonateur optique

Miroirs sphériques et modes Gaussiens

$$0 \leq \left(1 + \frac{d}{R_1}\right) \left(1 + \frac{d}{R_2}\right) \leq 1$$

Condition de stabilité d'un résonateur sphérique



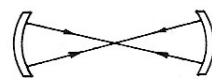
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Résonateur optique

Miroirs sphériques et modes Gaussiens



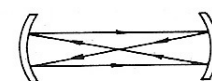
plane-parallel resonator
 $R_1 = R_2 = \infty$
 $g_1 g_2 = 1$



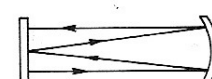
spherical resonator (concentric)
 $R_1 = R_2 = L/2$
 $g_1 g_2 = 1$



hemispherical resonator
 $R_1 = \infty, R_2 = L$
 $g_1 g_2 = 0$



confocal resonator
 $R_1 = R_2 = L$
 $g_1 g_2 = 0$

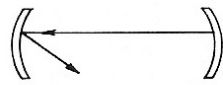


hemiconfocal resonator
 $R_1 = \infty, R_2 = 2L$
 $g_1 g_2 = 1/2$

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Résonateur optique

Miroirs sphériques et modes Gaussiens



$$R_1 = R_2 = L/3$$

$$g_1 g_2 = 4$$



$$R_1 = R_2 = -L$$

$$g_1 g_2 = 4$$



$$R_1 = L/2, R_2 = -L$$

$$g_1 g_2 = -2$$



$$R_1 = -L, R_2 = \infty$$

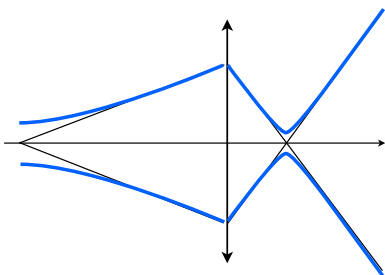
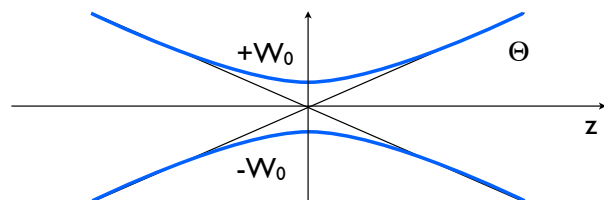
$$g_1 g_2 = 2$$

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Propagation

Optique modes Gaussiens

Apex, W_0
 Divergence, Θ_D
 Longueur de Rayleigh, z_R



$$W(z) = W_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

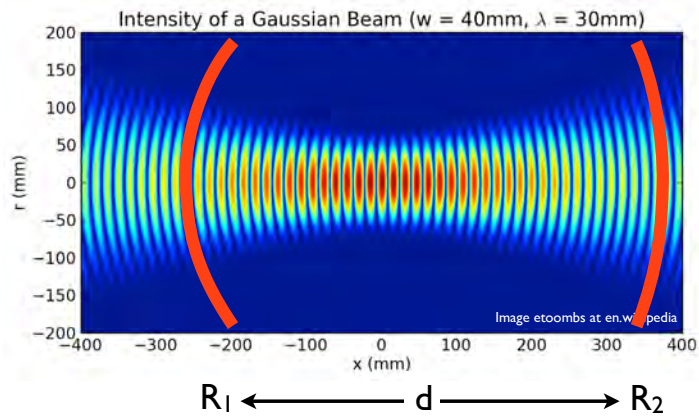
$$z_R = \frac{\pi W_0^2}{\lambda}$$

$$\Theta_D = \frac{\lambda}{\pi W_0}$$

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Résonateur optique

Miroirs sphériques et modes Gaussiens



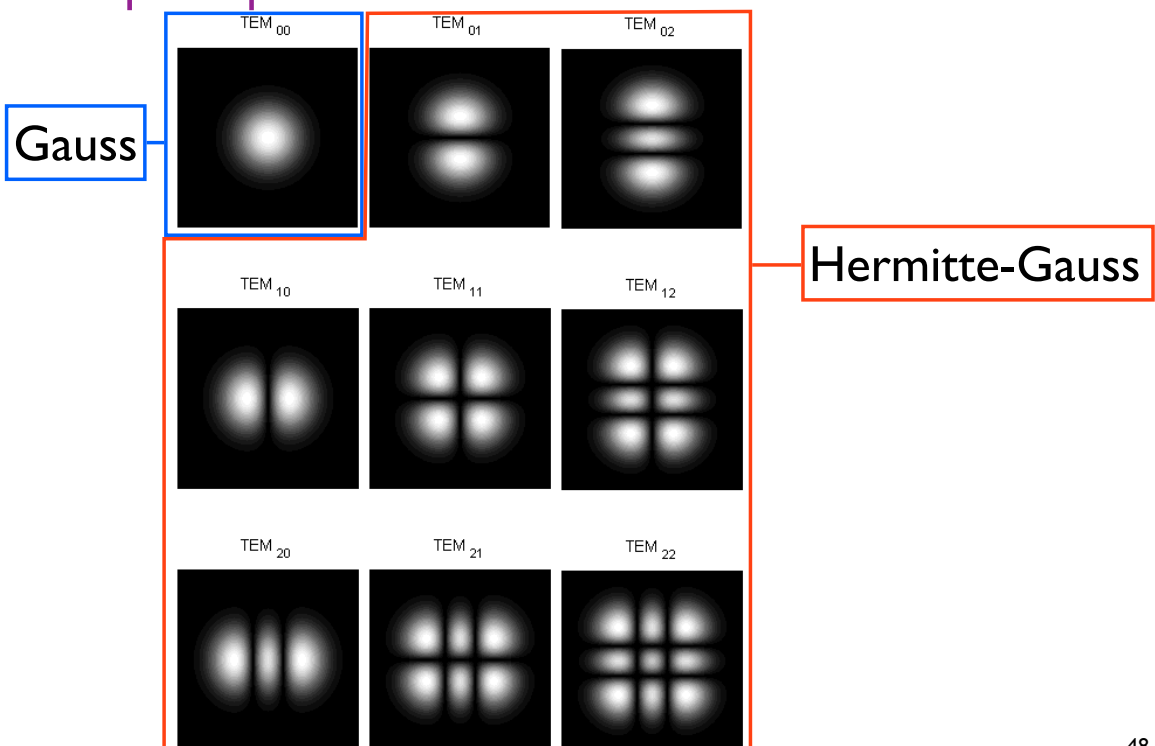
$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2}$$

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

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

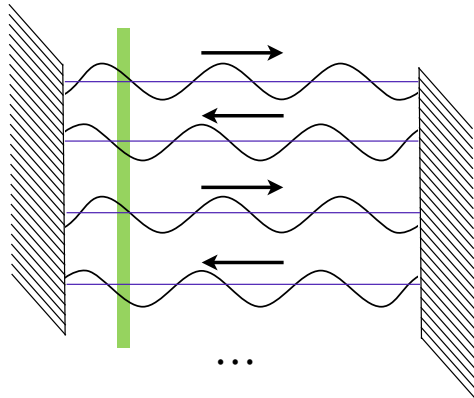
Résonateur optique

Miroirs sphériques et modes Gaussiens



Résonateur optique

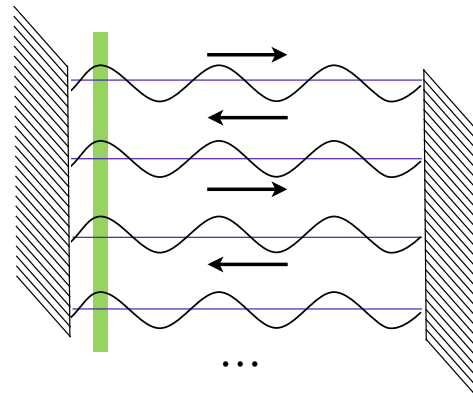
Ondulatoire, interférences



Alfred Perot
1863-1925



Charles Fabry
1867-1945

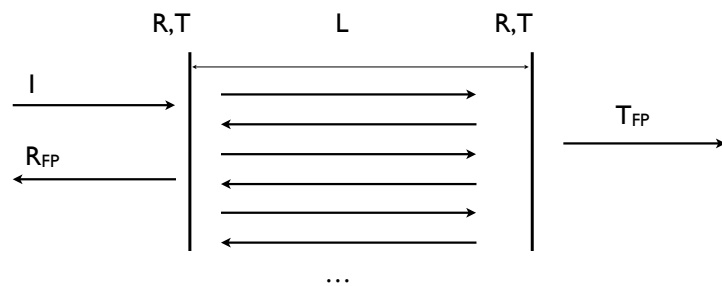


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Résonateur optique

Fabry-Perot

Rappel cours optique I



$$T_{FP} = \frac{T^2}{1 + R^2 - 2R \cos \phi}$$

$$\phi = 2kL = \frac{2\pi nL}{\lambda} = \frac{2\pi \nu nL}{c}$$

Déphasage sur un aller-retour

$$T_{FP} = \frac{T^2}{(1-R)^2 + 4R^2 \sin^2 \frac{\phi}{2}}$$

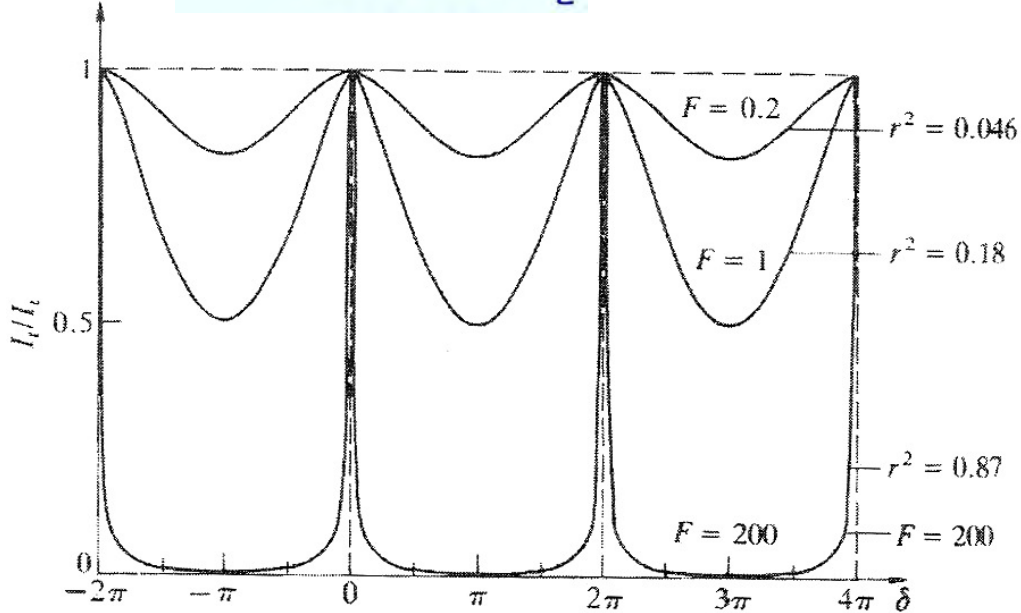
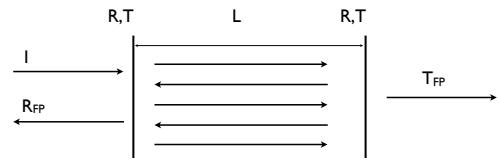
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Résonateur optique

Fabry-Perot

$$\phi = \frac{2\pi n L}{\lambda}$$

$$T_{FP} = \frac{T^2}{(1-R)^2 + 4R^2 \sin^2 \frac{\phi}{2}}$$



Résonateur optique

Fabry-Perot

$$\phi = \frac{2\pi n L}{\lambda}$$

$$T_{FP} = \frac{T^2}{(1-R)^2 + 4R^2 \sin^2 \frac{\phi}{2}}$$

$$\sin^2 \frac{\phi}{2} = 0 \quad \frac{1}{2} \frac{2\pi n_m L}{\lambda} = m\pi$$

$$\nu_m = \frac{mc}{2nL}$$

$$\Delta\nu = \frac{c}{2nL}$$

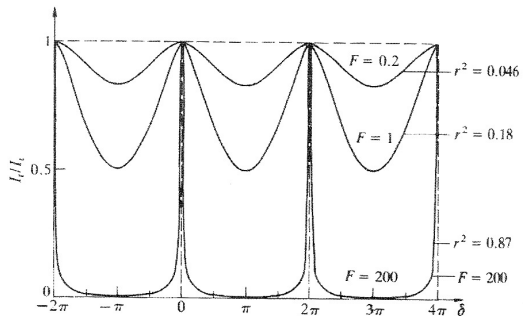
$$Q = \frac{\nu_m}{\delta\nu_m}$$

$$F = \frac{\Delta\nu}{\delta\nu_m} = \frac{\pi\sqrt{R}}{1-R}$$

Intervalle spectral libre

Facteur de qualité

Finesse



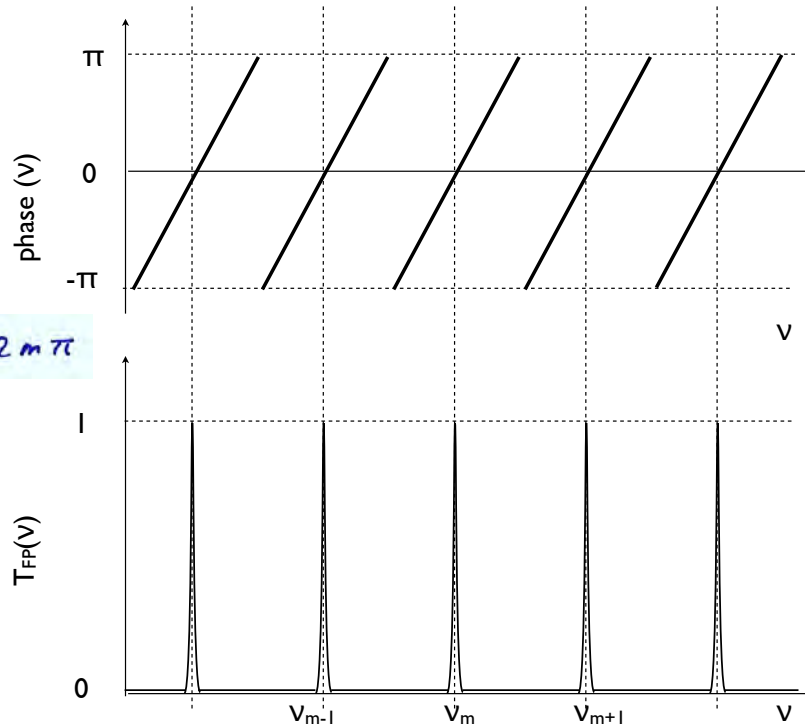
Résonateur optique

Fabry-Perot

$$\varphi = \frac{2\pi n \nu L}{c}$$

$$\sin^2 \frac{\varphi}{2} = 0$$

$$\varphi_m = 2k_m L = 2m\pi$$



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Résonateur optique

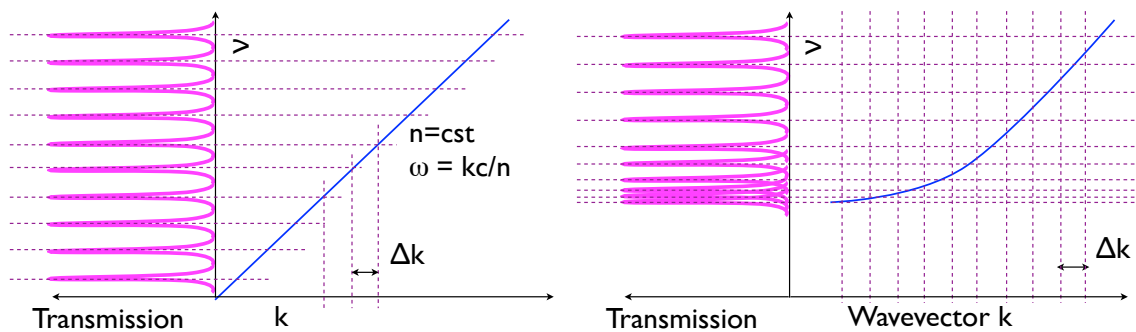
Fabry-Perot

$$\varphi = 2kL = \frac{2\pi n \nu L}{c}$$

indice de réfraction \Rightarrow

$$\nu_m n(\nu_m) = \frac{m c}{2L}$$

$$\varphi_m = 2k_m L = 2m\pi \Rightarrow \Delta k = \frac{\pi}{L}$$



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