Les Oscillateurs Paramétriques Optiques: fondements et Applications

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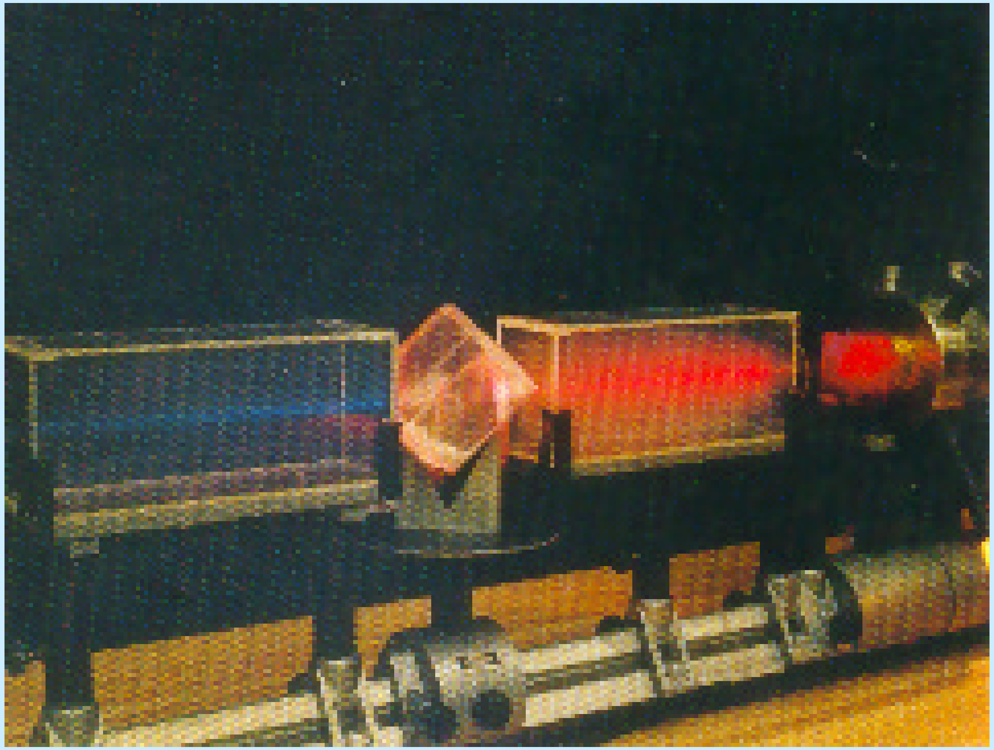
Tout a commencé comme ça…



T.H. Maiman, Nature (1960) → *P.A. Franken, A.E. Hill, C.W. Peters and G. Weireich, Phys. Rev. Lett. (1961)*

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- Modèle mécanique de l’optique non linéaire
- Equations de couplage paramétrique: aspect ondulatoire
- Equations de Manley-Rowe: aspect corpusculaire
- Amplification paramétrique
- Oscillation paramétrique optique
- Accord et quasi-accord de phase
- Comportement dynamique des OPO
- Quelques applications et développements actuels

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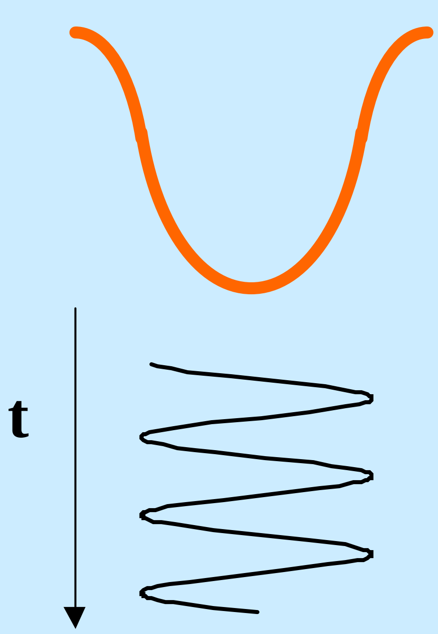
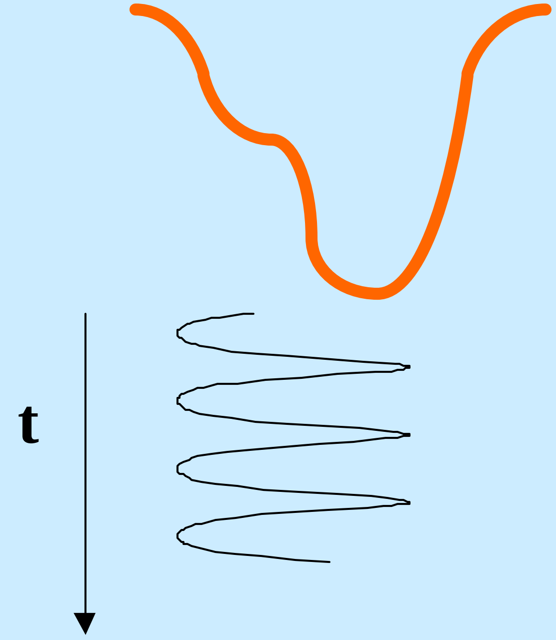
Optique non linéaire quadratique

SYSTEME SYMETRIQUE



SYSTEME NON SYMETRIQUE



Susceptibilité optique non linéaire

$$P(t) = e_0 \, c^{(1)} E(t) \quad + \quad e_0 \, c^{(2)} E(t)^2$$

w

2 w

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1. Modèle mécanique de l'optique non linéaire quadratique

Potentiel anharmonique

$$U(x) = \tfrac{1}{2} m w_0^2 x^2 + \tfrac{1}{3} m D x^3$$

Force d'excitation périodique:

$$F(t) = qE\cos(wt) = \frac{qE}{2}\left(e^{iwt} + cc\right)$$

Equation différentielle

$$\ddot{x} + g\,\dot{x} + w_0^2 x + D x^2 = \frac{qE}{2m}\left(e^{iwt} + cc\right)$$

Analyse harmonique de x(t)

$$x(t) = x_0 + x_1 e^{iwt} + x_2 e^{i2wt} + \dots + cc$$

Rectification optique (→ x_0)

Réponse linéaire: Indice absorption (→ x_1)

Génération de Seconde harmonique (→ $x_2 e^{i2wt}$)

1. Modèle mécanique de l'optique non linéaire quadratique

Réponse linéaire:

$$x_1 = \frac{q\,E}{m}\,\frac{1}{\left(w_0{}^2 - w^2\right) + i\,w\,g} \approx \frac{q\,E}{2\,w\,m}\,\frac{1}{\left(w_0 - w\right) + i\;g\;/\;2}$$

Polarisation du milieu:

$$P_1\left(t\right) = N\,q\,x_1\left(t\right) = \frac{N\,q\,x_1}{2}\left(e^{i\,w\,t} + cc\right)$$

$$P_1\left(t\right) = \frac{e_0}{2}\left(c_1^{\left(w\right)}\,E\;e^{i\,w\,t} + cc\right)$$

Par définition

Modèle de Lorentz:

$$c_1^{\left(w\right)} = \frac{N\,q^2}{2\,w\,m\,e_0}\;\frac{1}{\left(w_0 - w\right) + i\;g\;/\;2}$$

Identification terme à terme des termes en 2w

Polarisation non linéaire du milieu:

$$P_2(t) = N\,q\,x_2(t) = \frac{N\,q\,x_2}{2}\left(e^{i\,2w\,t} + cc\right)$$

$$P_2(t) = \frac{e_0}{2}\left(c_2^{(2w)}\,E^2\;e^{i\,2w\,t} + cc\right)$$

Par définition

Réponse non linéaire:

$$x_2 \approx \frac{q^2\,D}{2\,m^2}\,\frac{1}{\left[(w_0 - w) + i\,g/2\right]^2\left[(w_0 - 2w) + i\,{}^{2}\!/_{3}\,g\right]}$$

Susceptibilité quadratique optique:

$$c_2^{(2w)} = \frac{N\,q^3\,D}{24w^3\,m^2\,e_0}\;\frac{1}{\left[(w_0 - w) + i\,g/2\right]^2\left[(w_0 - 2w) + i\,{}^{2}\!/_{3}\,g\right]}$$

Double résonance à w_0 et $w_0/2$

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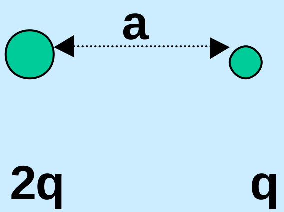
Règle de Miller:

Loin des résonnances

$$\frac{c_2^{(2w)}}{e_0^{\,2}\left(c_1^{(w)}\right)^2\left(c_1^{(2w)}\right)}=\frac{m\,D}{2\,N^2\,q^3}=d^{(2w)}$$

mat	n_1	n_2	c pm/V	d
GaSb	3.8	3.82	628	3.2 10^9
GaAs	3.27	3.30	368	5.4 10^9
ZnSe	2.42	2.43	78	8 10^9

Origine microscopique de la règle de Miller:



$$V(x)=\frac{-q^2}{4p\,e_0}\left(\frac{1}{x}+\frac{2}{a-x}\right)\approx\frac{-q^2}{4p\,e_0}\left(5.83+24\left(\frac{x}{a}\right)^2-17\left(\frac{x}{a}\right)^3\right)$$

$$D=-51\frac{q^2}{4p\,e_0\,m\,a^4}$$

Pour a = 0,5 nm alors D =2 10^{41} SI soit d = 6 10^{19} SI pour N = 6 10^{28} m^{-3}

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1. Modèle mécanique de l'optique non linéaire quadratique

Aspect tensoriel

$$\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = e_0 \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} {E_x}^2 \\ {E_y}^2 \\ {E_z}^2 \\ E_z E_y \\ E_z E_x \\ E_x E_y \end{bmatrix}$$

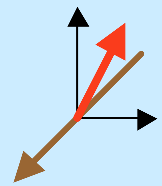
GaAs:

$$\begin{bmatrix} 0 & 0 & 0 & d_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{14} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{14} \end{bmatrix}$$

$$P_x = d_{14} \, E_{zy}$$

Pas de non linéarité le long des axes cristallographiques

Non linéarité le long de (110)

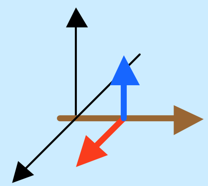


$NbLiO_3$:

$$\begin{bmatrix} d_{11} & -d_{11} & d_{13} & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & 0 & -d_{11} \\ d_{31} & d_{31} & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$P_z = d_{31} \, {E_x}^2$$

Non linéarité le long de (010)



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2. Équation de propagation de l'interaction non linéaire

$$\nabla . E = 0$$

$$\nabla . B = 0$$

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

$$\nabla \times B = m_0 \frac{\partial}{\partial t} \underbrace{\left(e_0 E + P\right)}_{D} = \frac{1}{c^2} \frac{\partial}{\partial t} E + \underbrace{m_0 \frac{\partial}{\partial t} P}_{\text{Courant de déplacement}}$$

Maxwell

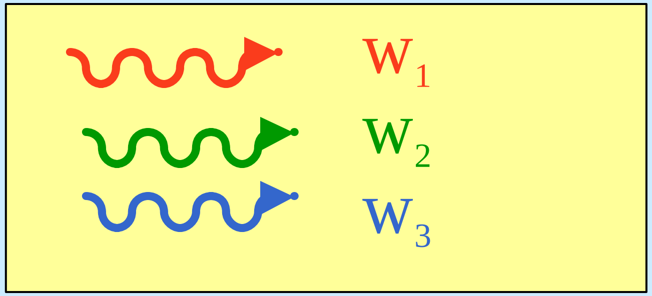
Polarisation linéaire et non linéaire: $P(t) = P_l(t) + P_{nl}(t) = e_0\, c_1\, E(t) + P_{nl}(t)$

Indice optique: $n_{op}{}^2 = 1 + c_1$

$$\nabla^2 E - \left(\frac{n_{op}}{c}\right)^2 \frac{\partial^2}{\partial t^2} E = m_0 \frac{\partial^2}{\partial t^2} P_{nl}(t)$$

. *Équation de propagation de l'interaction non linéaire*

Mélange à 3 ondes



$$\underbrace{\cos(w_1 t)\cos(w_2 t)}_{P_2(t)} \rightarrow \cos[\underbrace{(w_1+w_2)}_{\text{Somme De Fréquences}}t] \quad et \quad \cos[\underbrace{(w_1-w_2)}_{\text{Différence De Fréquence}}t]$$

Somme De Fréquences

Différence De Fréquence

Terme de somme de fréquences:

$$P_{nl}(z,t)=\frac{e_0\, c_2}{2}\left(\underbrace{E_2(z,t)^*}_{-W_2}\ \underbrace{E_3(z,t)}_{+W_3}+cc\right)$$

W_1 ← $-\ W_2$ $+\ W_3$

Transfert d'énergie entre les ondes

$$E_j(z,t)=\frac{1}{2}\left(\underbrace{E_j(z)}_{\text{Interaction Évolue lentement}}\underbrace{e^{i(w_j t-k_j z)}}_{\text{Ondes planes (sans interaction)}}+cc\right)$$

Interaction Évolue lentement

Ondes planes (sans interaction)

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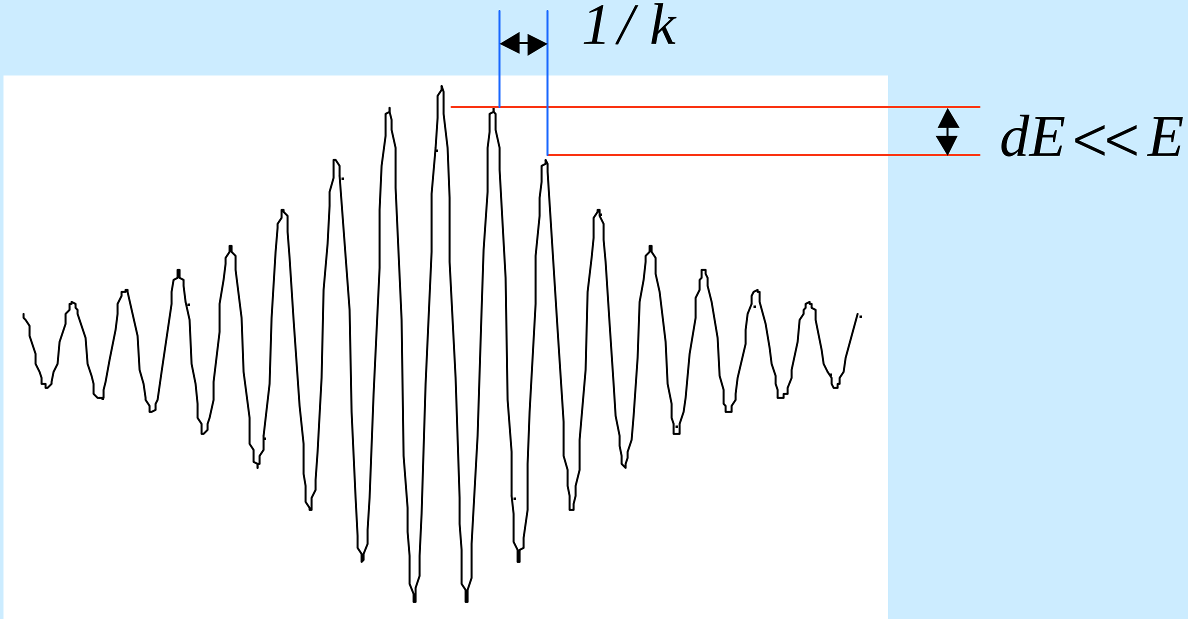
. Équation de propagation de l’interaction non linéaire

Approximation
de la Fonctions- enveloppe

$$\left|\frac{d^2 E_j}{dz^2}\right| << \left| k_j \frac{d E_j}{dz} \right|$$



$$w_3 - w_2 \rightarrow w_1 \qquad \frac{d}{dz} E_1 = -i \frac{w_1}{2 n_1 c} c_2 E_3 E_2^* e^{-i Dk z}$$

$$w_3 - w_1 \rightarrow w_2 \qquad \frac{d}{dz} E_2 = -i \frac{w_2}{2 n_2 c} c_2 E_3 E_1^* e^{-i Dk z}$$

$$w_1 + w_2 \rightarrow w_3 \qquad \frac{d}{dz} E_3 = -i \frac{w_3}{2 n_3 c} c_2 E_1 E_2 e^{+i Dk z}$$

Désaccord de phase $Dk = k_3 - k_1 - k_2$

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Doublage de fréquence $w_1 = w_2 = w \;\; et \;\; w_3 = 2w$

$2w - w \rightarrow w$

$$\frac{d}{dz} E_w = -i \frac{w}{2 n_w c} c_2 E_{2w} E_w^* e^{-i Dk z}$$

reconversion

$w + w \rightarrow 2w$

$$\frac{d}{dz} E_{2w} = -i \frac{w}{n_{2w} c} c_2 E_w^2 e^{+i Dk z}$$

Pompe non déplétée: $E_w(z) \approx E_0$

$$E_{2w}(z) = \frac{w}{n_{2w} c} c_2 E_0^2 L \, sinc\left(\frac{Dk\, l}{2}\right)$$

Rendement de conversion

$$P_{2w}(z) = 2 \frac{Z_0^3}{n_{2w} c} (w \, e_0 \, c_2 \, L)^2 \, sinc^2\left(\frac{Dk\, l}{2}\right) P_w^2$$

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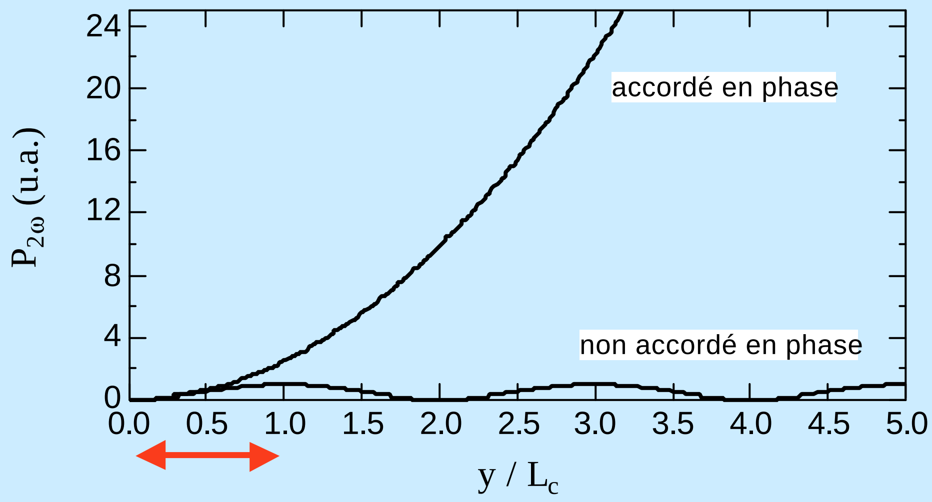
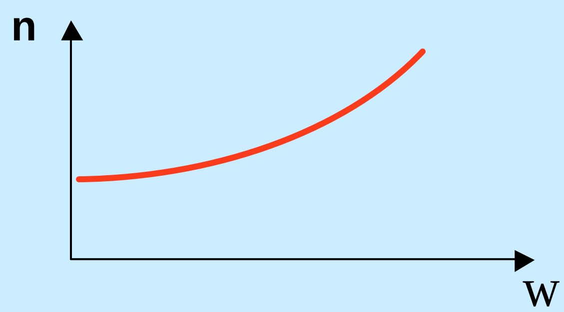
. Équation de propagation de l'interaction non linéaire: désaccord de phase dans le doublage de fréquence

$$P_{2w}(z) \propto L^2 \; sinc^2\left(\frac{Dk\, l}{2}\right) P_w{}^2$$



Longueur de cohérence:

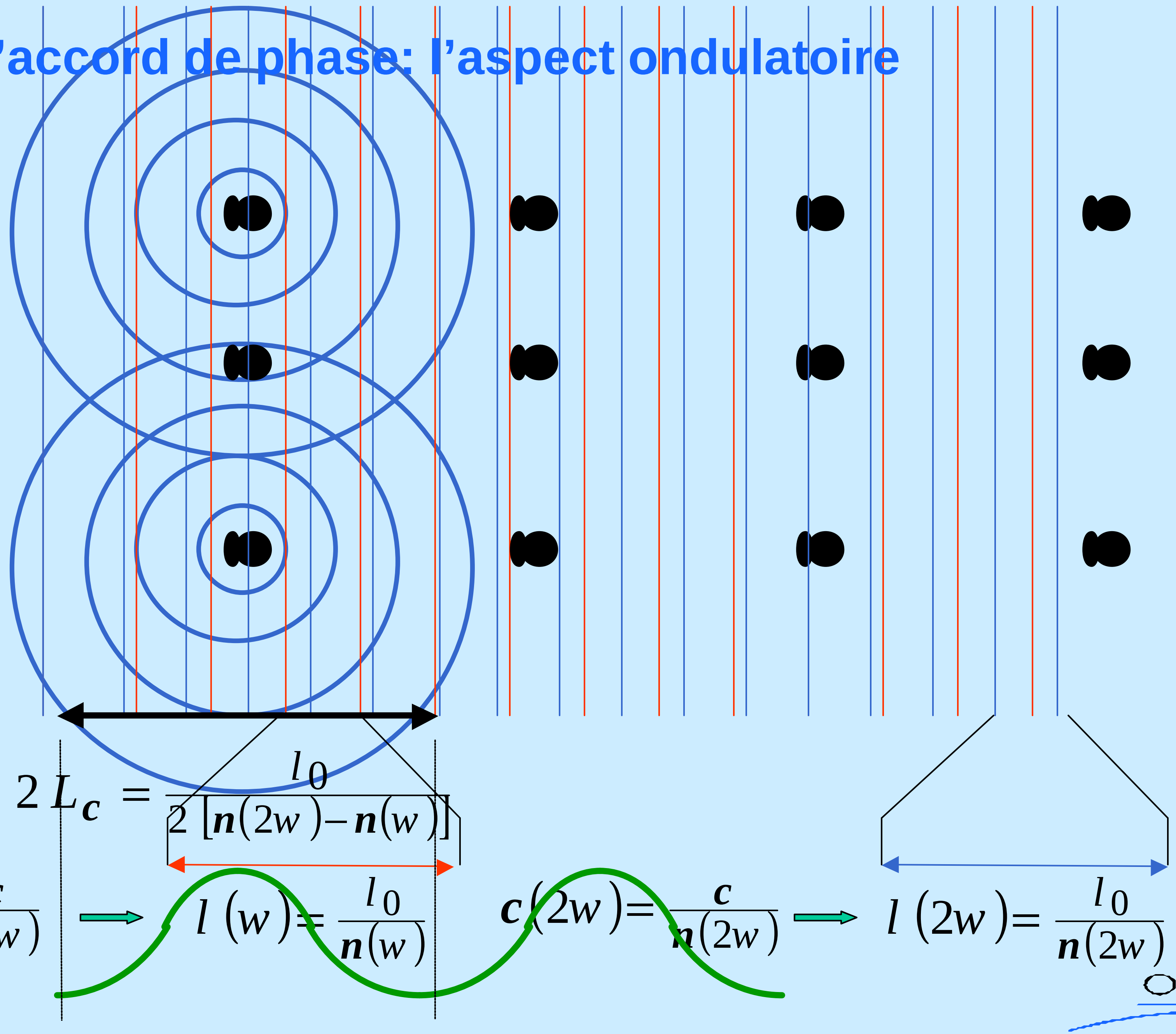
$$L_c = \frac{l_0}{4\,(n_{2w} - n_w)}$$



dispersion

Exemple: dans GaAs
Fondamental 10,6 µm ® GSH 5,3 µm
c = 100 pm/V
$n_2 - n_1 = 2,5\ 10^{-2}$
L_c=106 µm
$P_2 = 10^{-11}\ P_1{}^2$ (W/cm²)

L’accord de phase: l’aspect ondulatoire



$$2\,L_c = \frac{\lambda_0}{2\,[\boldsymbol{n}(2\omega) - \boldsymbol{n}(\omega)]}$$

$$\boldsymbol{c}(\omega) = \frac{\boldsymbol{c}}{\boldsymbol{n}(\omega)} \rightarrow \lambda(\omega) = \frac{\lambda_0}{\boldsymbol{n}(\omega)}$$

$$\boldsymbol{c}(2\omega) = \frac{\boldsymbol{c}}{\boldsymbol{n}(2\omega)} \rightarrow \lambda(2\omega) = \frac{\lambda_0}{\boldsymbol{n}(2\omega)}$$

3. Equations de Manley-Rowe: aspect corpusculaire

abracadabra…: $$A_j = \sqrt{\frac{n_j}{w_j}}\, E_j$$

→

***Amplitude de flux de photons*:**

$$F_j = \frac{P_j}{\hbar w_j} = \frac{1}{2\hbar Z_0} \left| A_j \right|^2$$

$$w_3 - w_2 \rightarrow w_1 \qquad \frac{d}{dz} A_1 = -i k\, A_3\, A_2^{*}\, e^{-i Dk\, z}$$

$$w_3 - w_1 \rightarrow w_2 \qquad \frac{d}{dz} A_2 = -i k\, A_3\, A_1^{*}\, e^{-i Dk\, z}$$

$$w_1 + w_2 \rightarrow w_3 \qquad \frac{d}{dz} A_3 = -i k\, A_1\, A_2\, e^{+i Dk\, z}$$

***avec*:** $$k = \frac{1}{2}\frac{c_2}{c}\sqrt{\frac{w_1 w_2 w_3}{n_1 n_2 n_3}}$$

. Équations de Manley-Rowe: aspect corpusculaire

Si : $Dk = 0$ →

$$\frac{d}{dz}\left(|A_1|^2\right) = \frac{d}{dz}\left(|A_2|^2\right) = -\frac{d}{dz}\left(|A_3|^2\right)$$

$$\frac{d}{dz}(F_1) = \frac{d}{dz}(F_2) = -\frac{d}{dz}(F_3)$$

Manley-Rowe: conservation du flux de particules

Interprétation corpusculaire

$$\hbar w_3 = \hbar w_1 + \hbar w_2$$ **conservation de l'énergie**

$$\hbar k_3 = \hbar k_1 + \hbar k_2$$ **conservation de l'impulsion**

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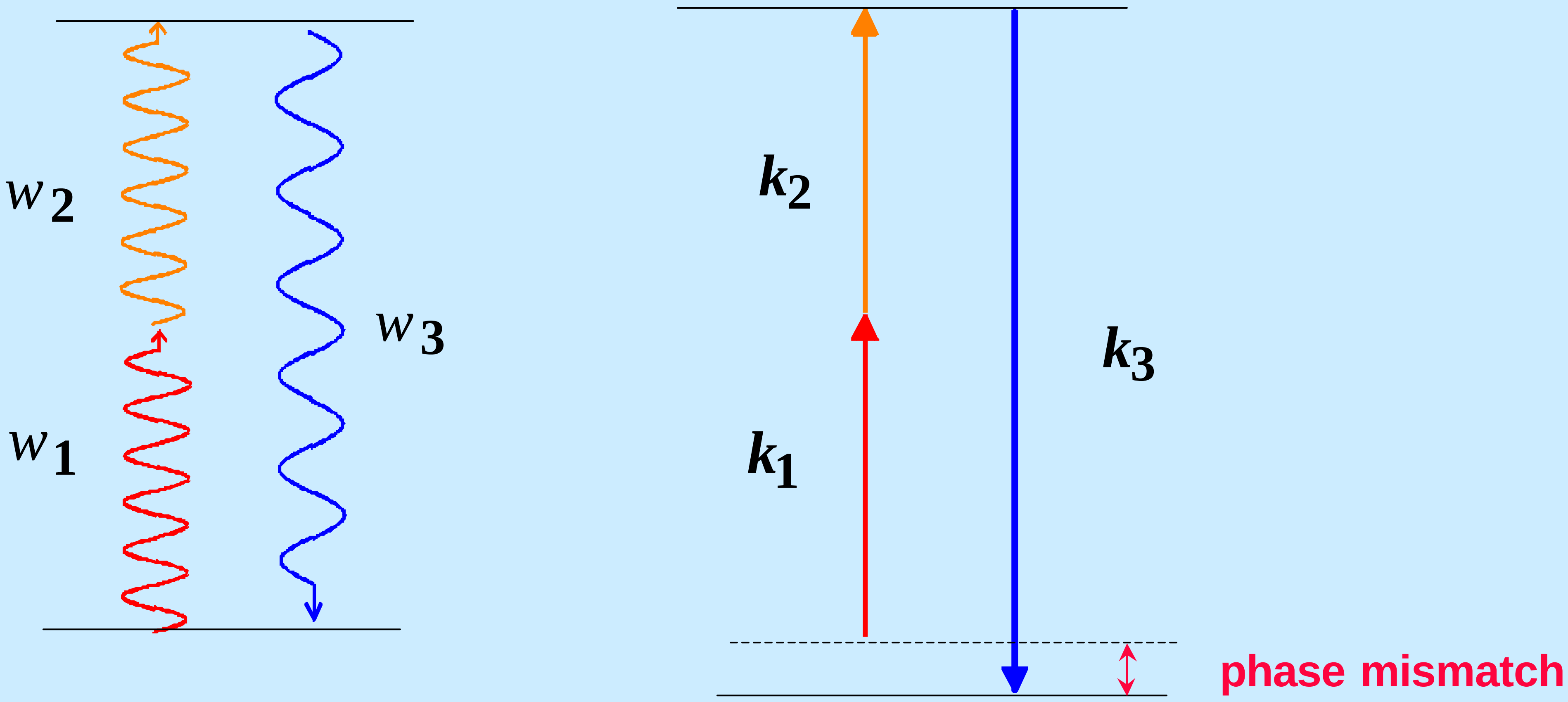
THE PHASE MATCHING PROBLEM: THE PHOTON ASPECT



energy conservation

momentum conservation

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4. L'amplification paramétrique

Hypothèse de la pompe non appauvrie
avec accord de phase

$$\frac{d}{dz} A_1 = -i\, g\, A_2^{\,*}$$

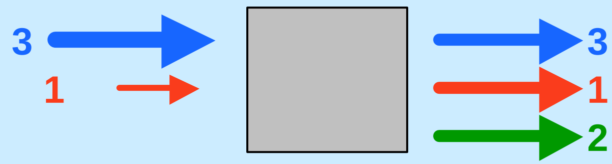
$$\frac{d}{dz} A_2 = -i\, g\, A_1^{\,*}$$

Avec le gain paramétrique

$$g = \frac{1}{2}\frac{c_2}{c}\sqrt{\frac{w_1 w_2}{n_1 n_2}}\, E_3(0)$$

$$A_1(z) = A_1(0)\,Cosh(g\,z) - i\; A_2(0)^*\; Sinh(g\,z)$$

$$A_2(z) = A_2(0)\,Cosh(g\,z) - i\; A_1(0)^*\; Sinh(g\,z)$$



Pour des gains paramétriques forts

$$A_1(z) \approx A_2(z) \approx \tfrac{1}{2} A_1(0)\, e^{g\,z}$$

Exemple: dans GaAs pour 5 MW/ cm²
Fondamental 5,3 µm ® 10,6 µm
c = 100 pm/V
G= 0,35 cm^{-1}

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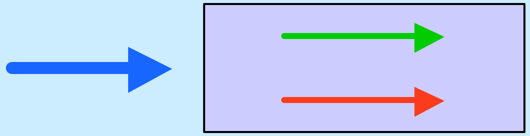
4. *L’amplification paramétrique*

Génération et fluorescence paramétrique optique



$$|n_1, n_2, n_3\rangle \Rightarrow |n_1+1, n_2+1, n_3-1\rangle$$

Hypothèse de la pompe non appauvrie
sans accord de phase

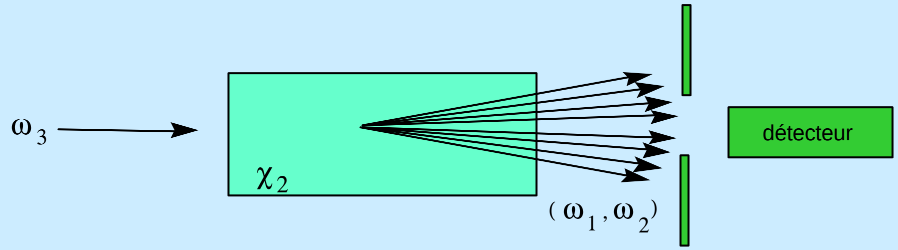
$$\frac{d}{dz}A_1 = -i\,g\,A_2^{*}\,e^{-iDk\,z}$$

$$\frac{d}{dz}A_2 = -i\,g\,A_1^{*}\,e^{-iDk\,z}$$

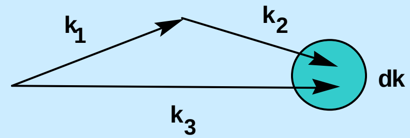
Avec le gain paramétrique

$$g = \sqrt{g^2 - (Dk)^2}$$

$$A_2(z)^{*} = i\,\frac{g}{g}\,A_1(0)\,Sinh(g\,z)\,e^{iDk\,z}$$



(a)



(b)

$A_1(0)$ **correspond à un seul photon par mode**

Génération et fluorescence paramétrique optique

Calcul effroyable:

Nombre de modes w_1 **entrant acceptable pour** w_3
on met un photon w_1 **par mode et on utilise le résultat de la planche précédente**

On somme sur toutes les paires acceptables tombant dans l'angle de vue q **du détecteur**

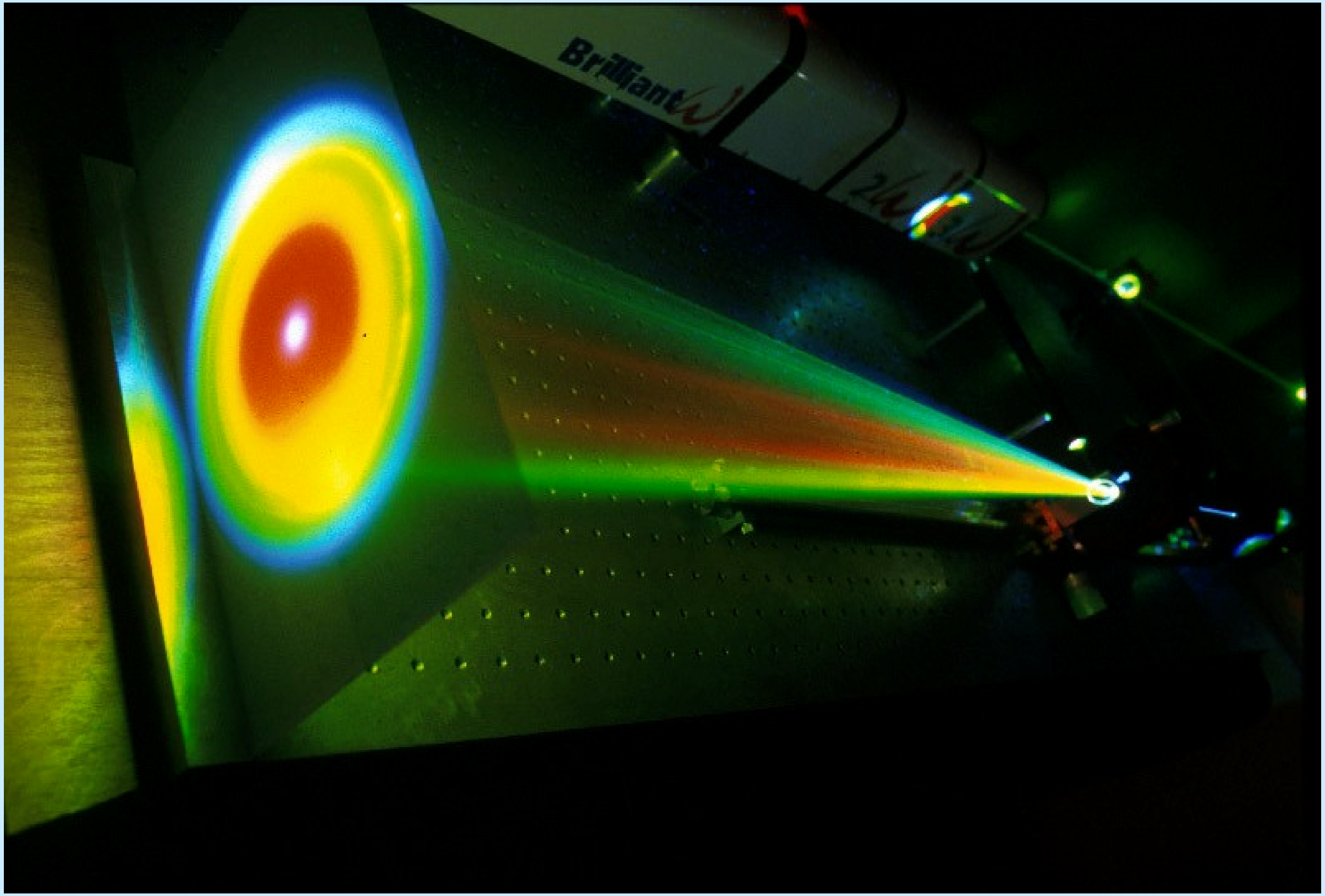
$$P_2 = p \frac{b\ L P_3}{|b|} q^2$$

$$b = \frac{\hbar w_1 w_2^4 n_2 c_2^2}{p^2 c^5 n_1 n_3 e_0^3}$$

$$b = \left.\frac{\partial k_2}{\partial w_2}\right|_{w_{20}} - \left.\frac{\partial k_1}{\partial w_1}\right|_{w_{10}}$$

Utilisation:

- **précurseur de l'oscillation paramétrique**
- **courbe d'accord de phase expérimentaux**



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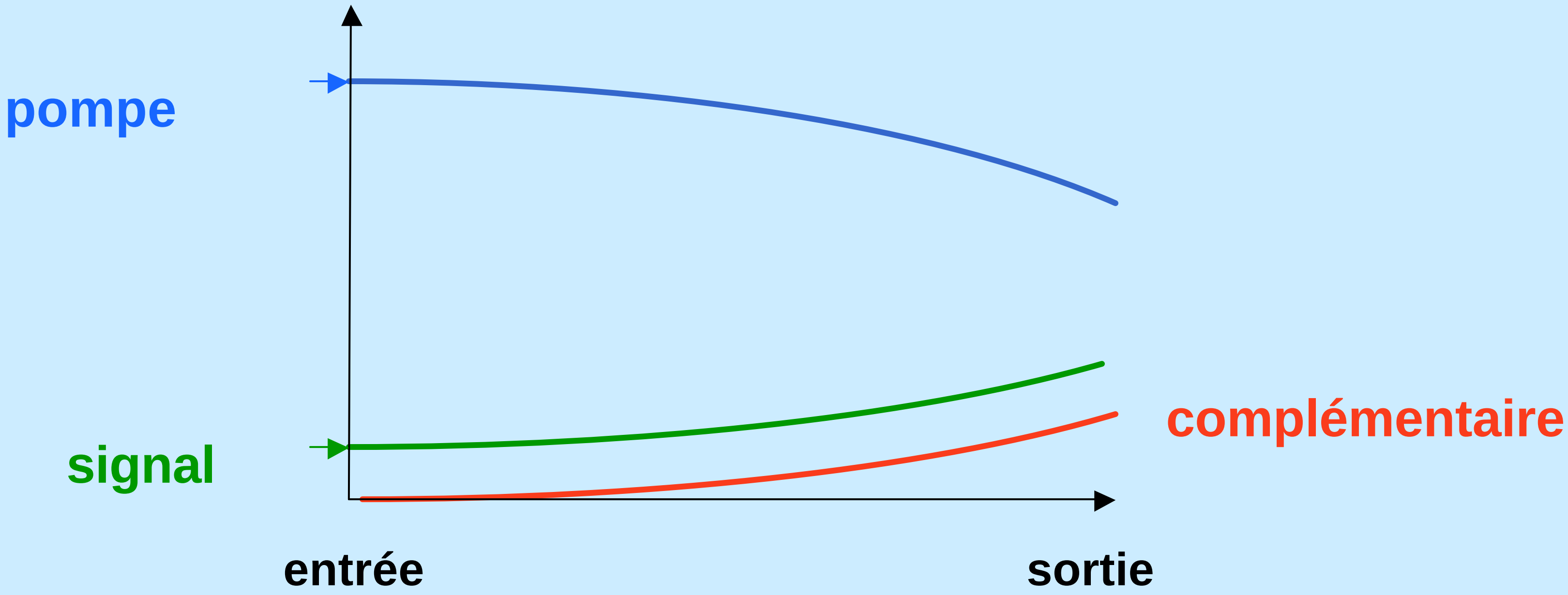
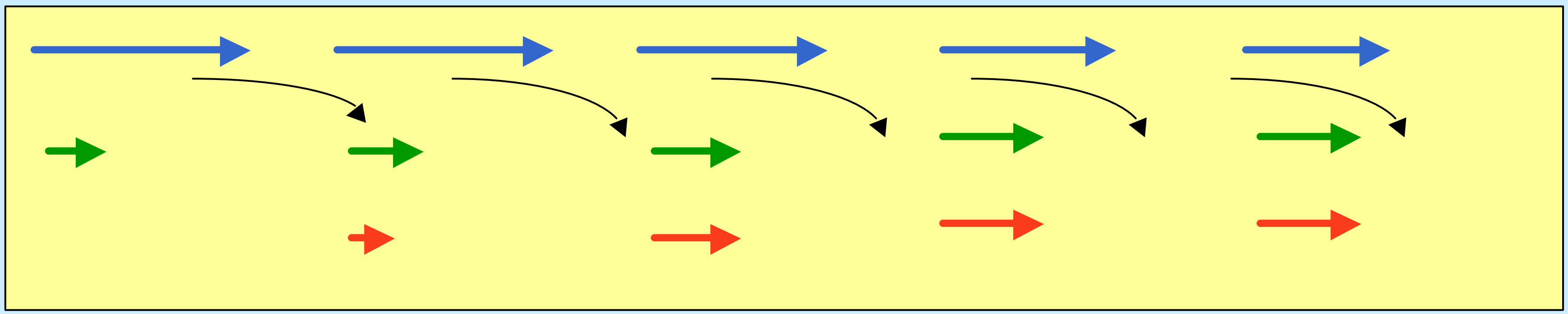
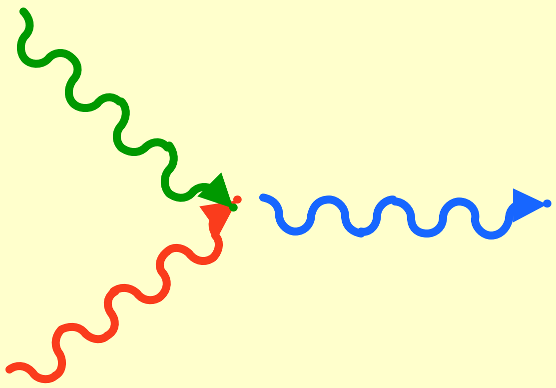
AMPLIFICATION ET FLUORESCENCE PARAMETRIQUE

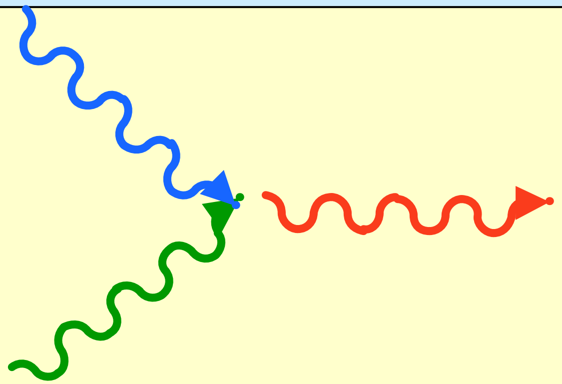




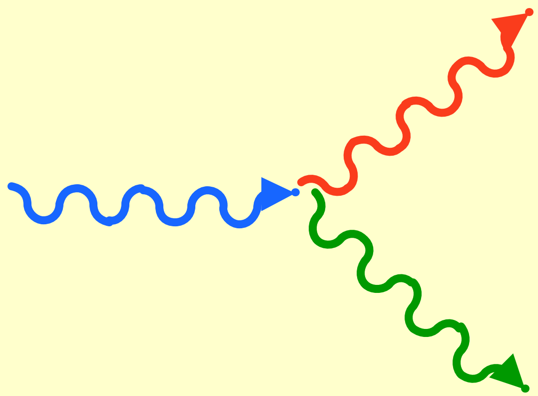
Sum and Difference Frequency Generation
vs parametric interaction



Sum Frequency Generation



Difference Frequency Generation



Optical Parametric Generation

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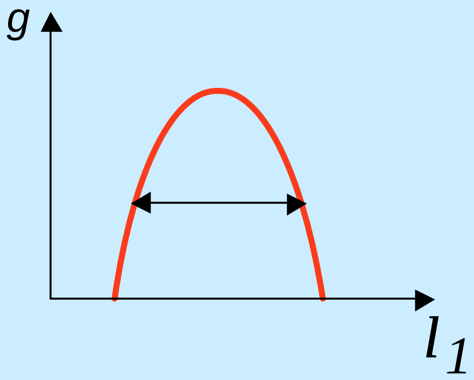
Largeur de gain paramétrique

$$\Delta k\, L = \pm \pi$$

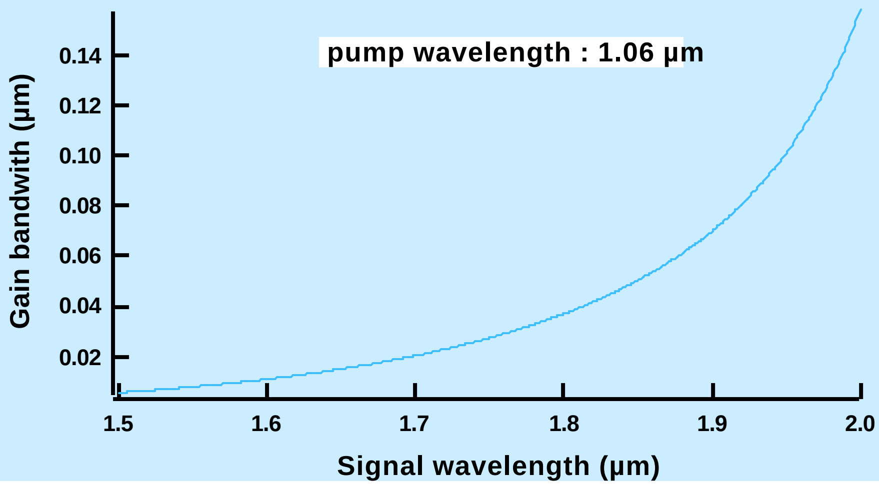


ccord de phase $$\frac{\Delta k}{2\pi} = \frac{n(\lambda_3)}{\lambda_3} - \frac{n(\lambda_1)}{\lambda_1} - \frac{n(\lambda_2)}{\lambda_2} = 0$$

Conservation de l'énergie $$\frac{1}{\lambda_3} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2}$$

La pompe λ_3 **est fixée**

$$\Delta\lambda_1 = \frac{\lambda_1^{2} / L}{\left(n_1 - n_2 + \frac{d\, n(\lambda_2)}{d\lambda_2}\lambda_2 - \frac{d\, n(\lambda_1)}{d\lambda_1}\lambda_1 \right)}$$



Accord de type I: polar. identique pour 1 et 2
Accord de type II: polar. différente pour 1 et 2

Niobate de lithium
Accord de type I

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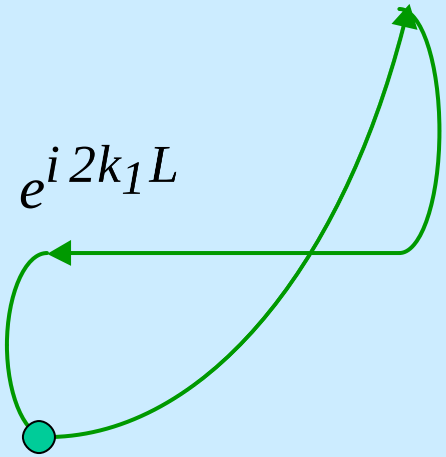
5. l'oscillateur paramétrique simplement résonant

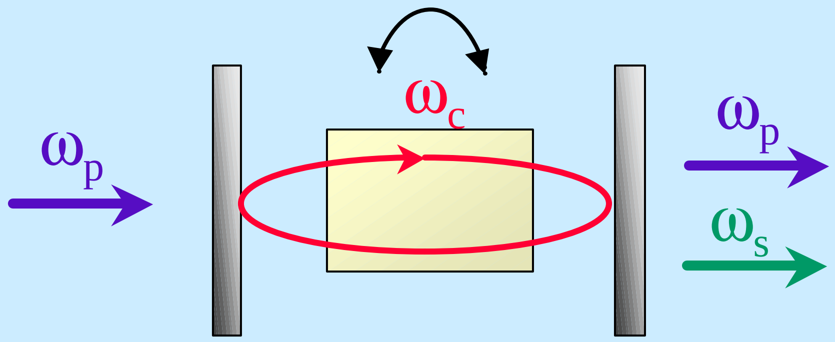


$$A_1(0)=r_e\, r_s \cosh(g\, L)e^{i\, 2 k_1 L}\, A_1(0)$$

$$Cosh\left(g_{seuil} L\right)=\frac{1}{\sqrt{R_e\, R_s}}$$ **Condition sur l'amplitude de pompe**

$$k_1\, L = m\, p$$ **Condition de résonance**

Optical Parametric Oscillator: basic principles



$\omega_s + \omega_c = \omega_p$ (energy conservation)

$k_s + k_c = k_p$ (phase matching condition)

1.064 µm → 1.4 ✸ 1.6 µm

1.064 µm → 3 ✸ 5 µm

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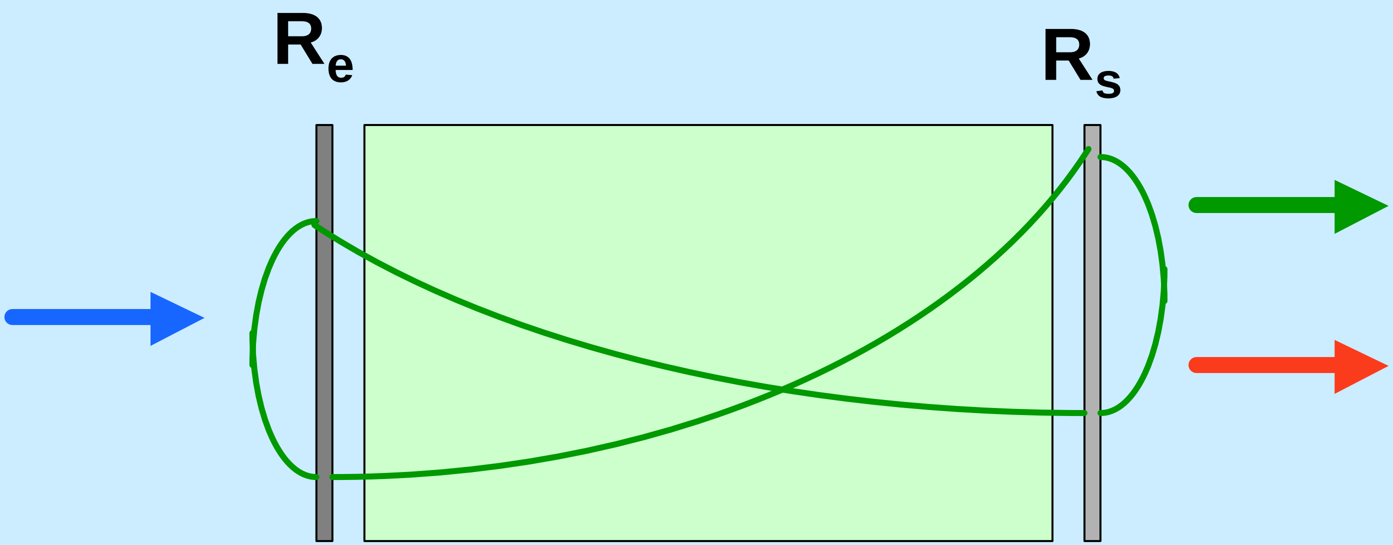
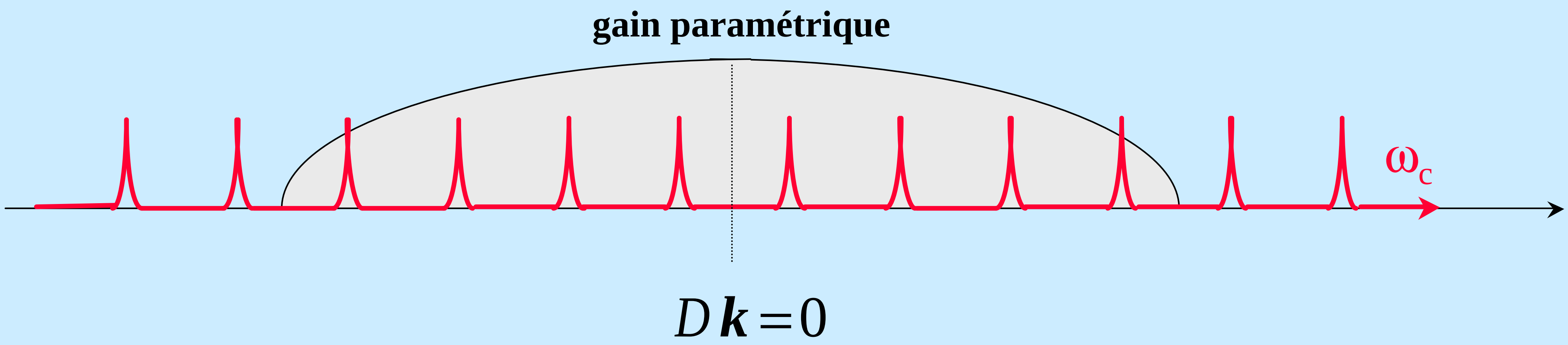
SINGLY RESONANT OPO (SROPO)



SEUIL:

gain = perte

$$g\left(I_{pompe}\right)L \approx \sqrt{T}$$



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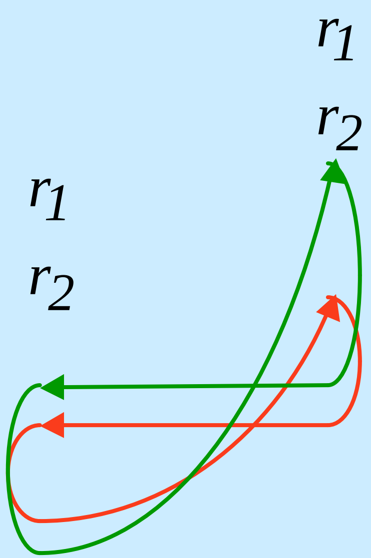
5. l'oscillateur paramétrique doublement résonant



$$A_1(0)=\left[A_1(0)\,Cosh(g\,L)-i\;A_2(0)^*\,Sinh(g\,L)\right]r_1^2\,e^{i\,2\,k_1\,L}$$

$$A_2(0)=\left[A_2(0)\,Cosh(g\,L)-i\;A_1(0)^*\,Sinh(g\,L)\right]r_2^2\,e^{i\,2\,k_2\,L}$$

$$det\begin{bmatrix} r_1^2\,cosh(gL)e^{i2k_1L}-1 & -i\,r_1^2\,sh(gL)e^{i2k_1L} \\ i\,r_2^2\,sh(gL)e^{i2k_2L} & r_2^2\,cosh(gL)e^{i2k_2L}-1 \end{bmatrix}=0$$

$$Cosh(g_{seuil}\,L)=\frac{1+R_1\,R_2}{R_1+R_2}$$

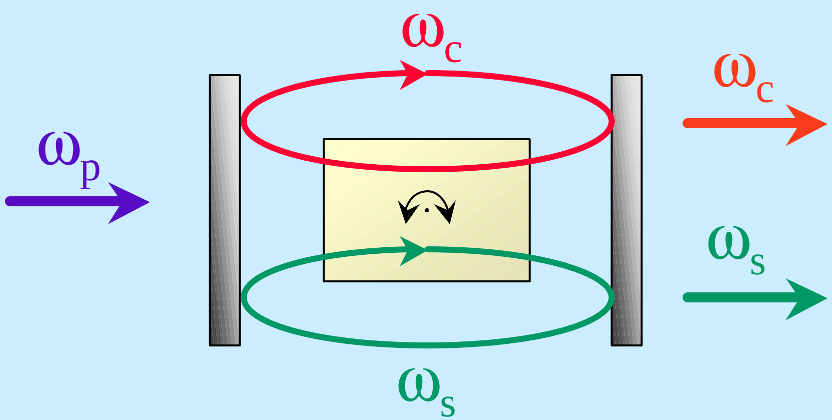
Condition sur l'amplitude de pompe

$$k_1\,L=m\,p$$

$$k_2\,L=n\,p$$

Conditions de résonance

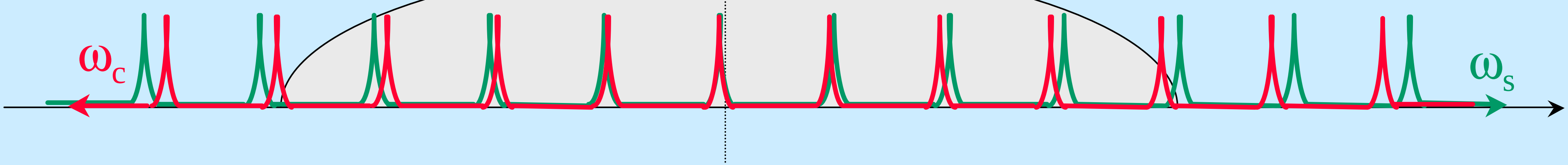
DOUBLY RESONANT OPO (DROPO)



SEUIL:

gain = perte

$$g\left(I_{pompe}\right)L \approx \sqrt{T_s T_c}$$



$$\Delta \boldsymbol{k} = 0$$

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5. l'oscillateurs paramétriques optiques: 2 exemples

GaAs : c = 100 pm/V
n = 3.2
l = 5 µm
L = 5 mm accordé en phase

SROPO: $R_e = R_s = 99\%$

$$Cosh\left(g_{seuil} L\right) \approx \sqrt{1-R_1}$$ → $P_{seuil} = 6\ MW/cm^2$

DROPO: $R_e = R_s = 99\%$

$$Cosh\left(g_{seuil} L\right) \approx \sqrt{\left(1-R_1\right)\left(1-R_2\right)}$$ → $P_{seuil} = 0{,}2\ MW/cm^2$

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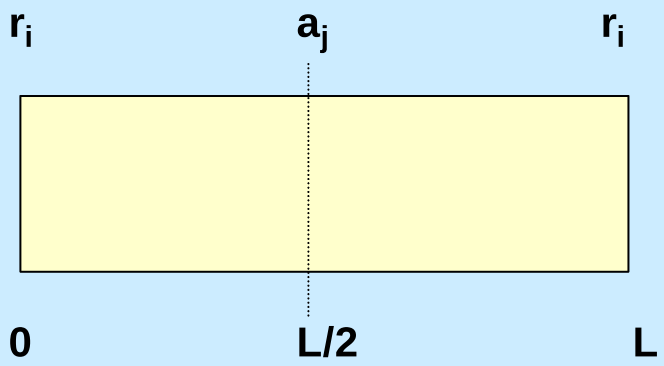
6. Comportement dynamique des OPO



Linéarisation des équations

$$u_i^n(L) = u_i^n(L/2) \pm \frac{k\,L}{2} u_j^n(L/2) u_k^n(L/2)$$

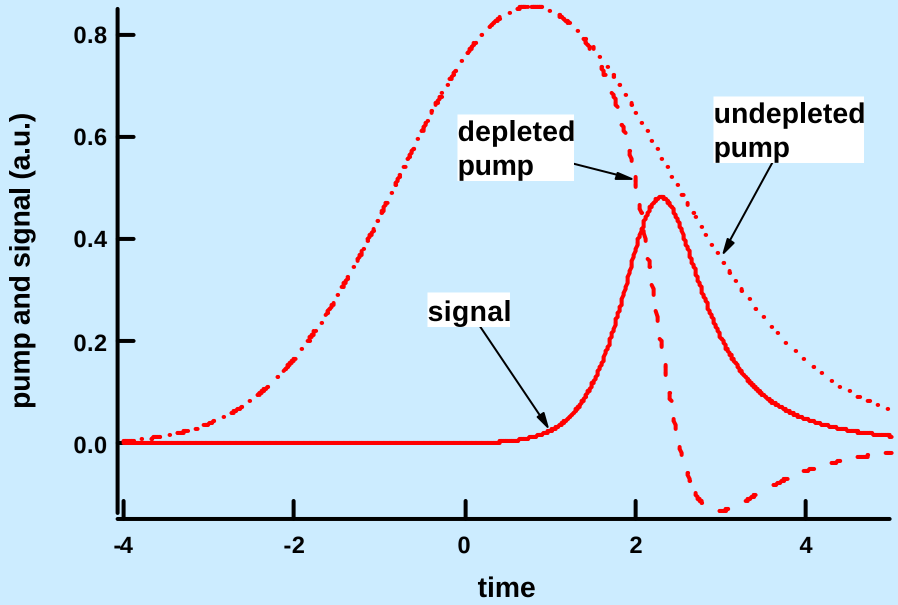
$$\frac{d}{dt} a_1(t) = -\frac{a_1}{t_1} + g_1 a_2 a_3$$

$$\frac{d}{dt} a_2(t) = -\frac{a_2}{t_2} + g_2 a_1 a_3$$

$$\frac{d}{dt} a3(t) = f(t) - \frac{a_3}{t_3} - g_3 a_1 a_2$$

avec

$$t_j = \frac{T_{AR}}{1 - r_j} \quad \text{et} \quad g_j = (1 + r_j)\frac{k\,c'}{4}$$



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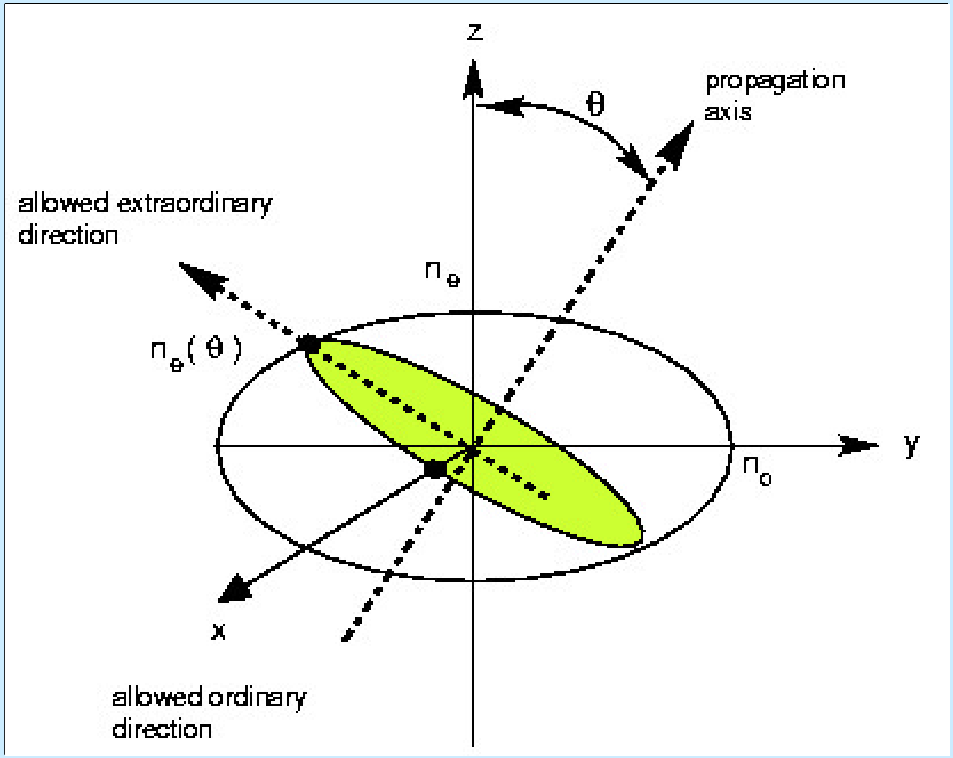
7.a Accord de phase par biréfringence

Cristal biréfringent d'axe optique Oz

n_o ***Indice ordinaire (Ox, Oy)***

n_e ***Indice extraordinaire (Oz)***

$$\frac{1}{n_e^{\,2}(q)} = \frac{cos^2 q}{n_o^{\,2}} + \frac{sin^2 q}{n_e^{\,2}}$$



Une onde se propage dans zOy avec un angle avec l'axe optique: deux directions de propagation de polarisation linéaire

- L'indice ordinaire (le long de Ox) est indépendant de l'angle q_s

- L'indice extraordinaire dépend de l'angle q_s

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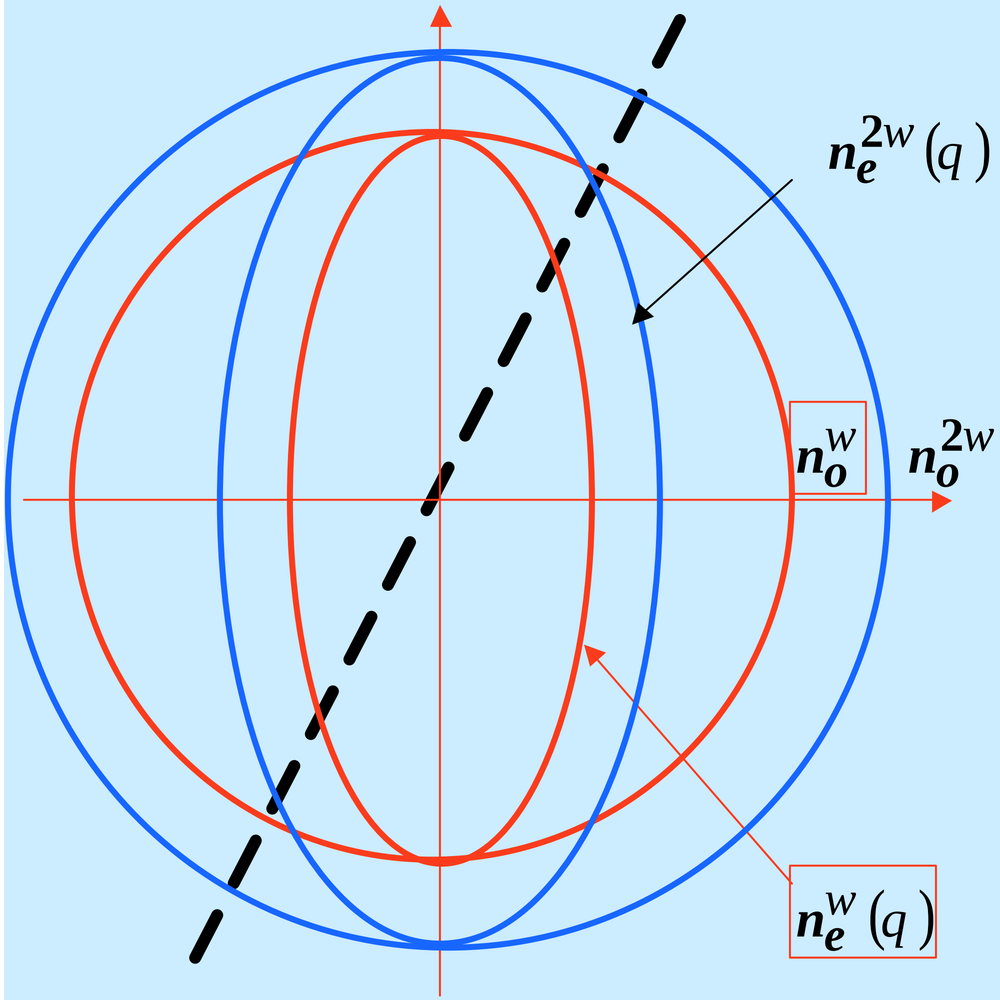
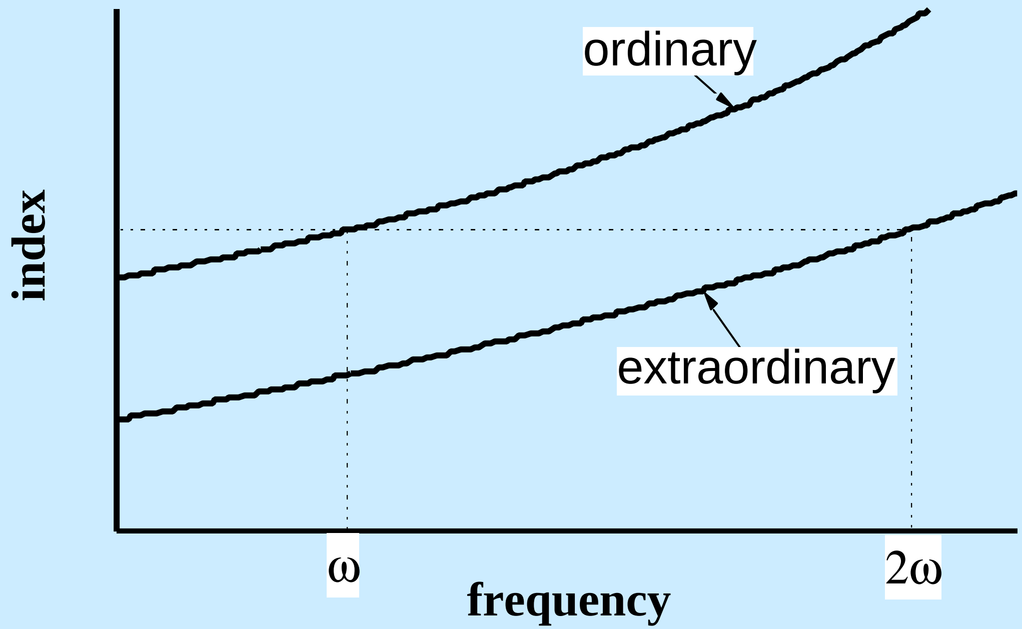
Accord de phase par biréfringence





Milieu uniaxe négatif

$$n_e^{2w}(q) = n_o^{w}(q) \;\; Þ \;\; \textit{accord de phase}$$

7.a Exemple : doublage dans le niobate de lithium

$$n_e(2w, q_s) = n_o(w) \quad \Longrightarrow \quad \frac{1}{n_o(w)^2} = \frac{cos^2 q_s}{n_o(2w)^2} + \frac{sin^2 q_s}{n_e(2w)^2}$$

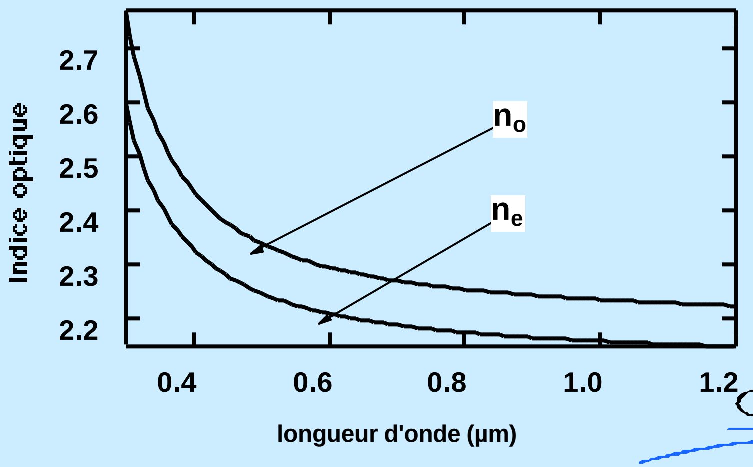
Relation de Sellmeier

$$n^2 = A - \frac{B}{C - l^2} - D\, l^2$$

	A	B	C	D
n_e	4.5820	0.099169	0.044432	0.021950
n_o	4.9048	0.11768	0.04750	0.027169

Exemple : 1,3 µm ® 0,65 µm

q_s = 45°



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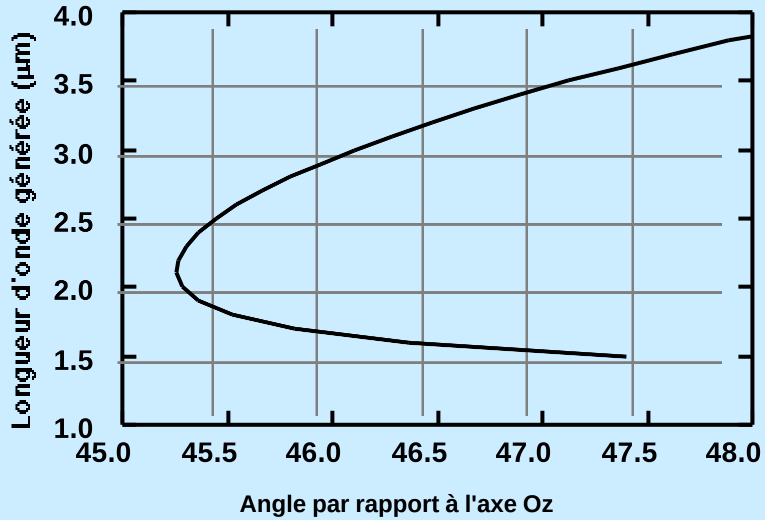
7.a Exemple : oscillation paramétrique dans le niobate de lithium

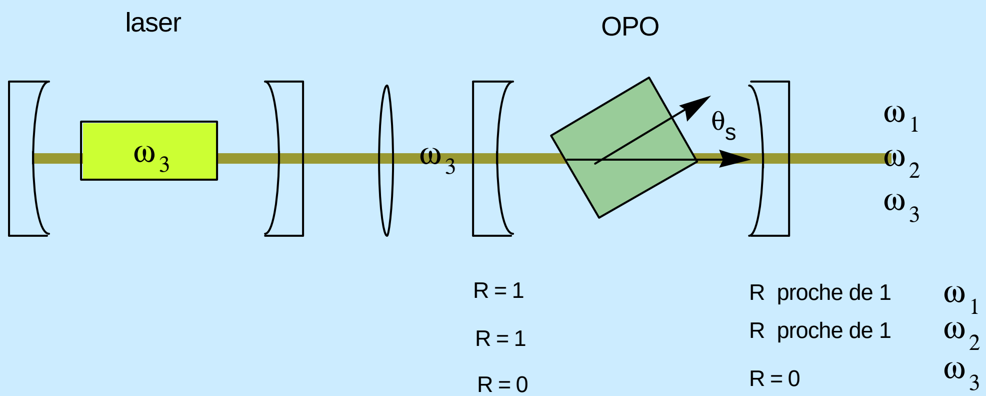
Accord de phase ® eeo

$$w_1 + w_2 = w_3$$

$$n_o(w_1)w_1 + n_o(w_2)w_2 = n_e(w_3, q_s)w_3$$



Accord de longueur d'onde par rotation



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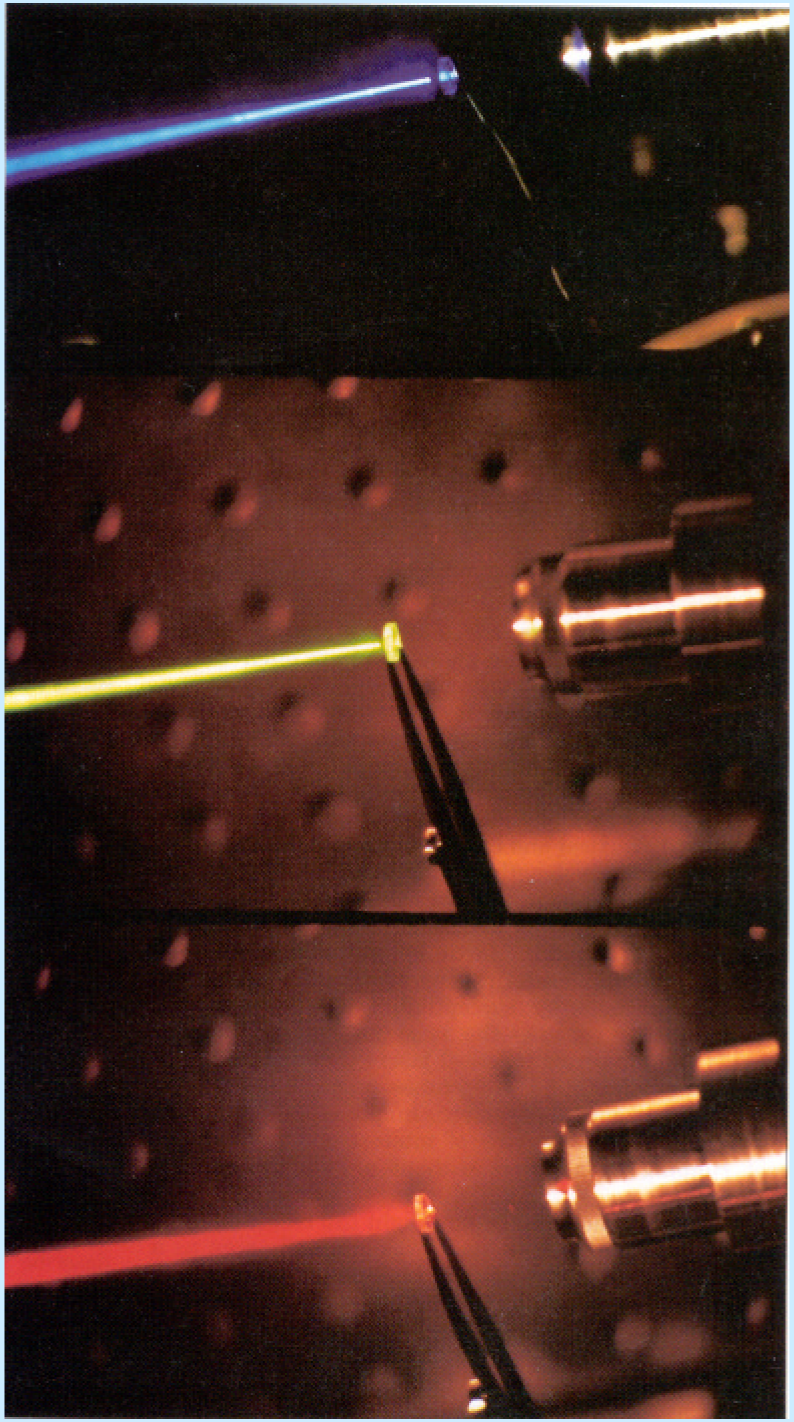
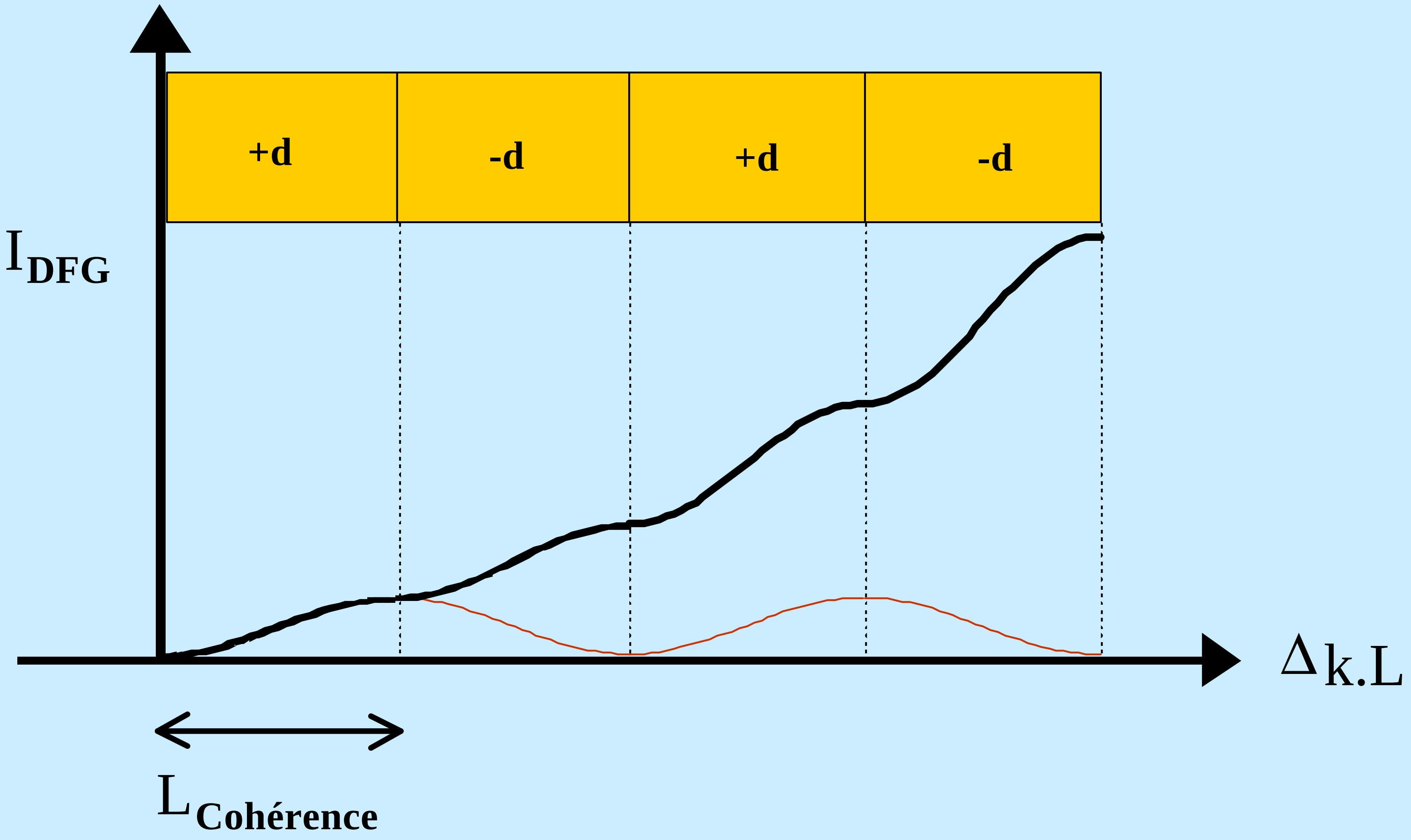
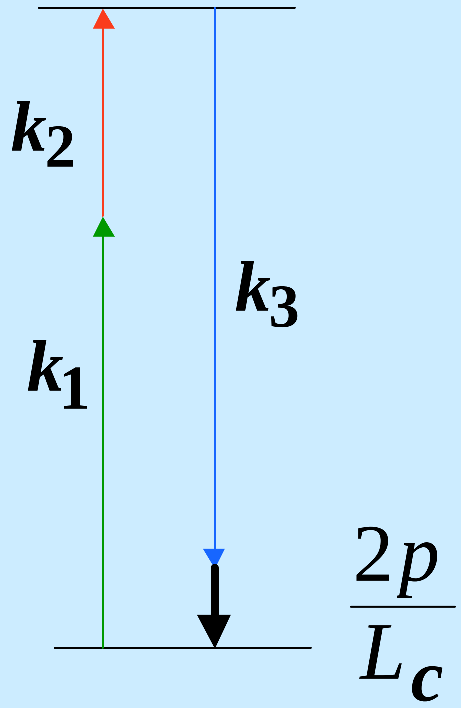


7.b First order quasi-phase matching





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7.b le quasi accord de phase

Indice non linéaire modulé $c_2(z) = c_2 \; f(z)$ **avec** $f(z) = \sum_n f_n e^{in(2p/L)z}$

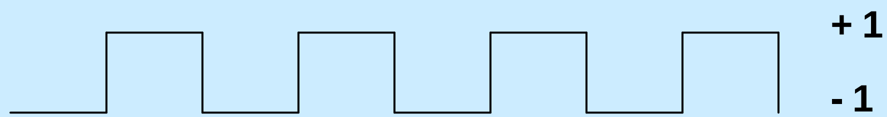
Pompe non appauvrie $\frac{d}{dz} E_{2w} = -i \frac{w}{n_{2w} c} c_2 E_w^2 \; f(z) e^{+iDk\,z}$

$$\Rightarrow \quad E_{2w}(z) = -i \frac{w}{n_{2w} c} c_2 E_w^2 \int_0^L f(z) e^{+iDk\,z} dz$$

Seul terme non nul $k_{2w} - 2k_w = n \frac{2p}{L}$ **soit** $L = (2n+1) L_c$

Susceptibilité effective $c_2^{eff} = c_2 \left| f_n \right| = \frac{2}{p} c_2$

$f(z)$



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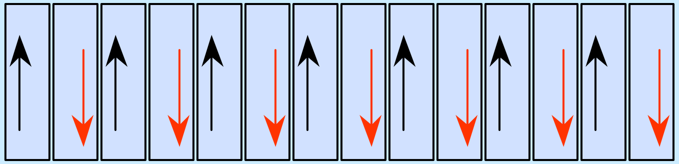
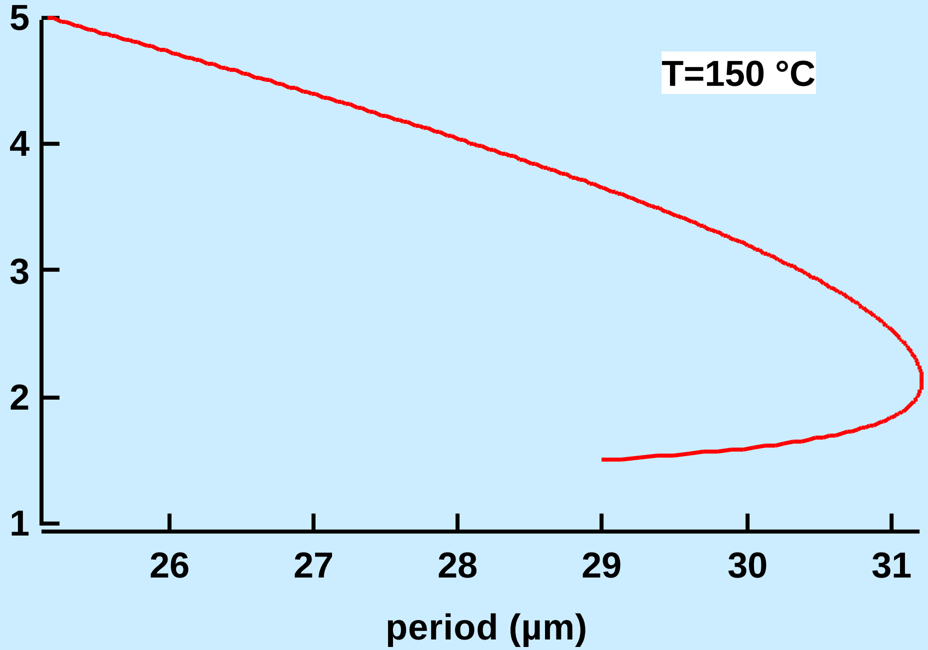
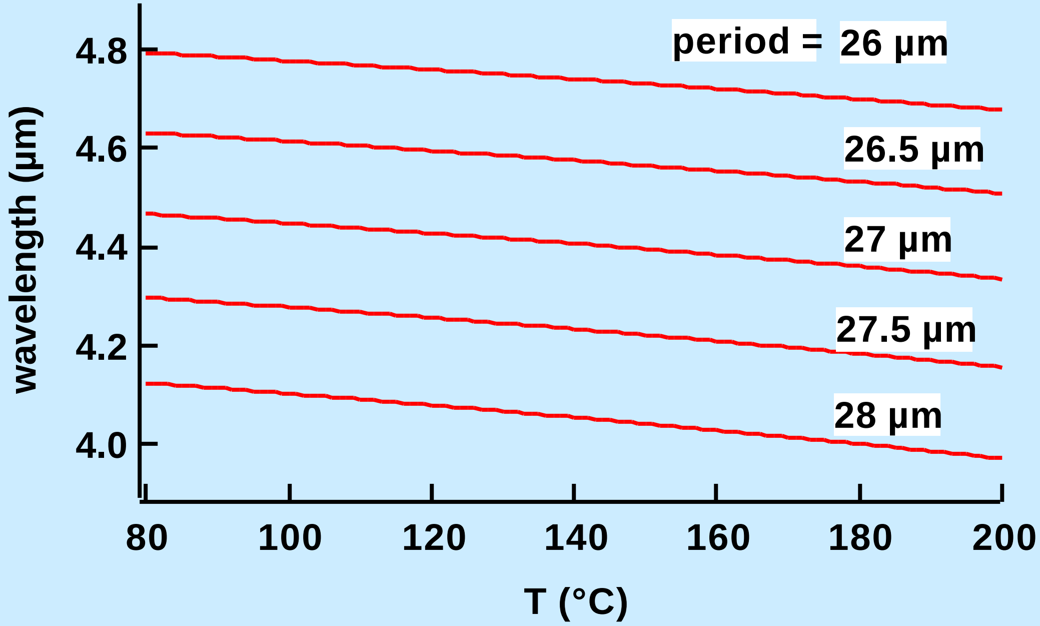
Periodically Poled Lithium Niobate







wavelength vs period **wavelength vs T**

d_{eff} = 27 pm/V !!!!!!

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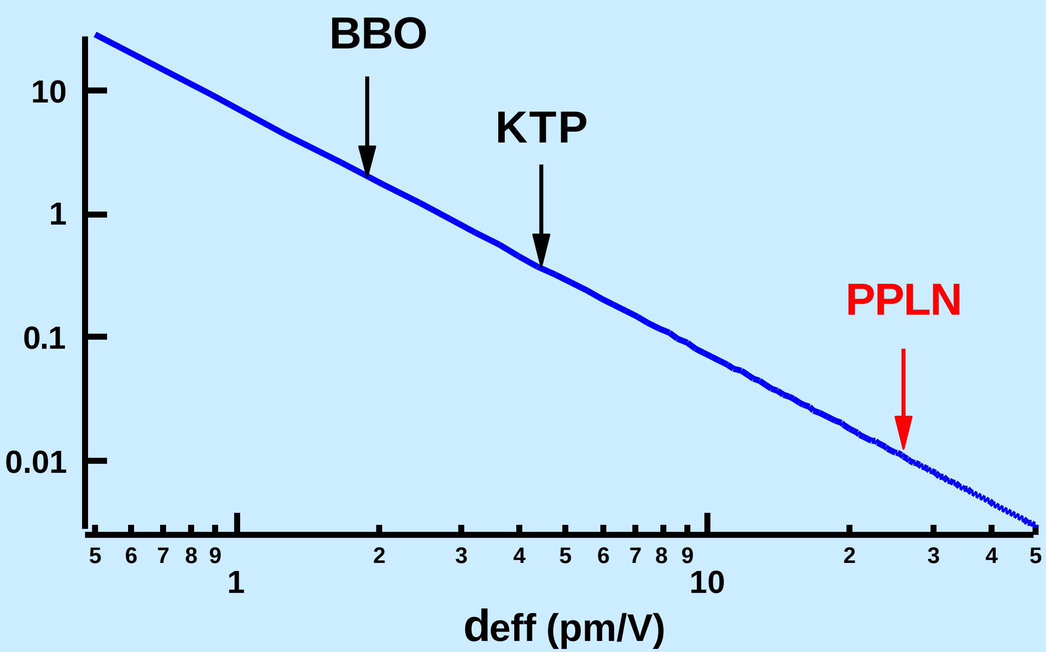
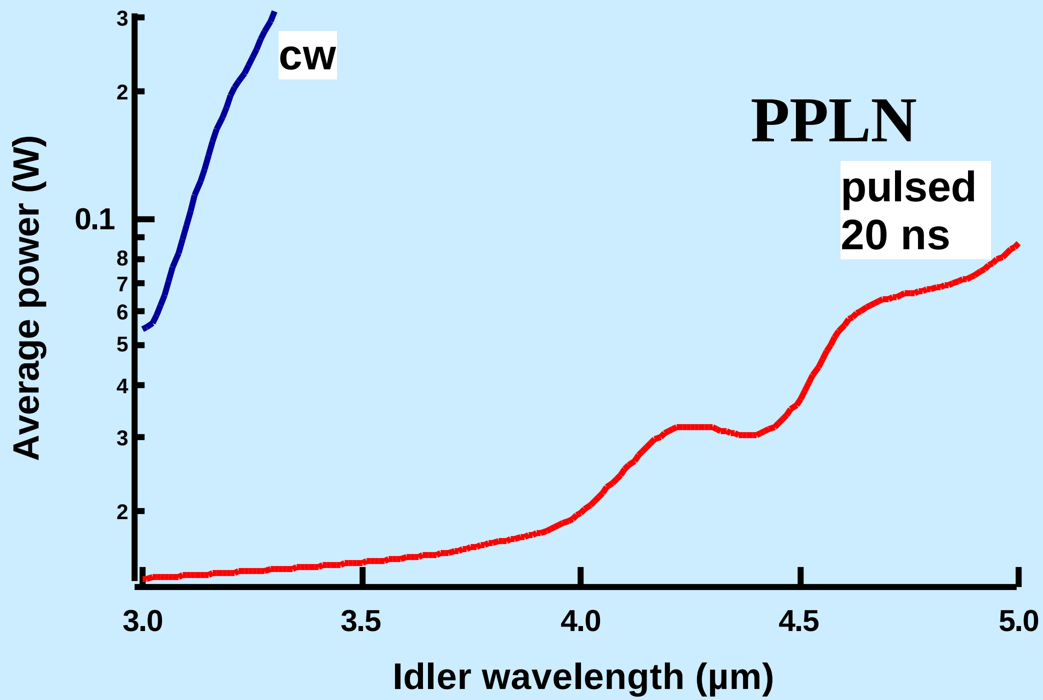
Optical Parametric OscillatorThreshold: PPLN breakthrough





Gaussian pulse ;DROPO, $\Phi = 40$ µm;
f = 10 kHz ; $L_{cav} = 2$ cm

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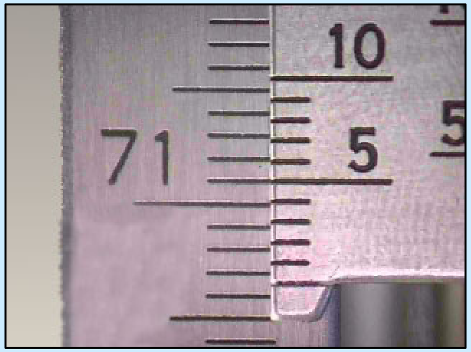
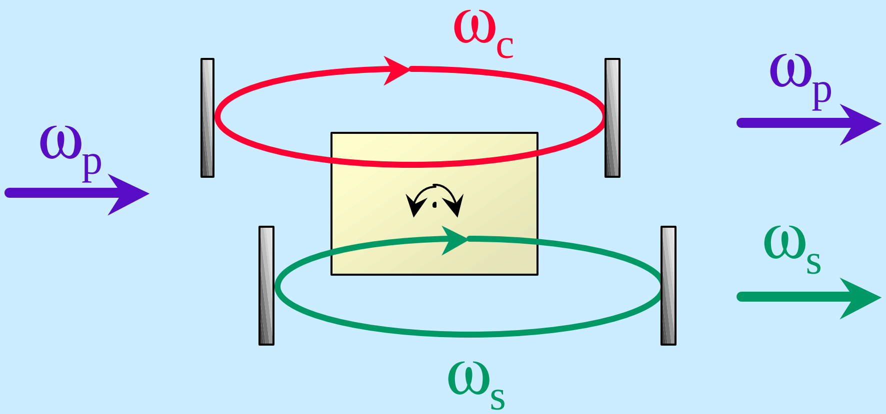
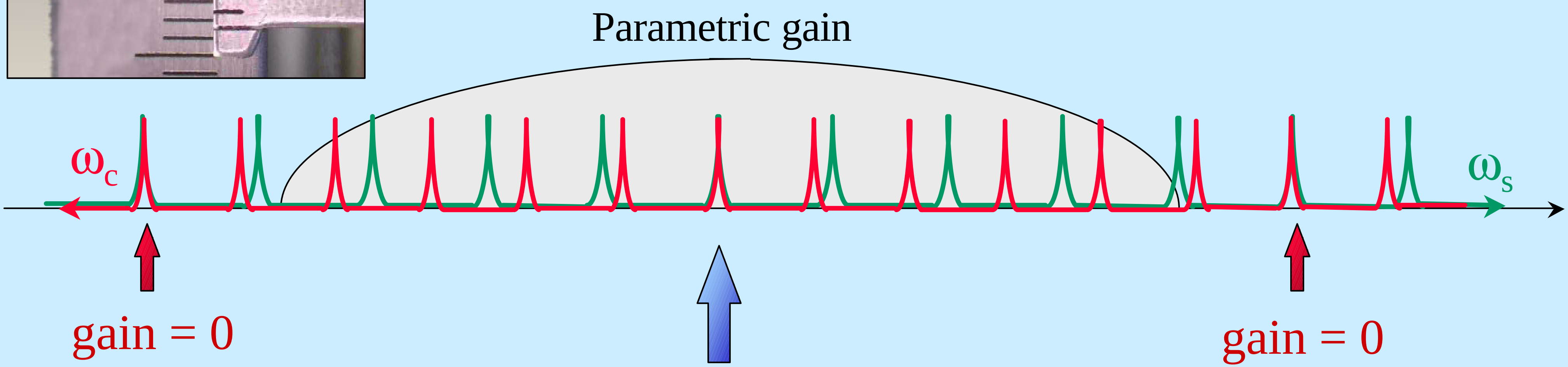
8. Quelques développements récents

Entangled Cavity
Doubly resonnant OPO







Single frequency emission

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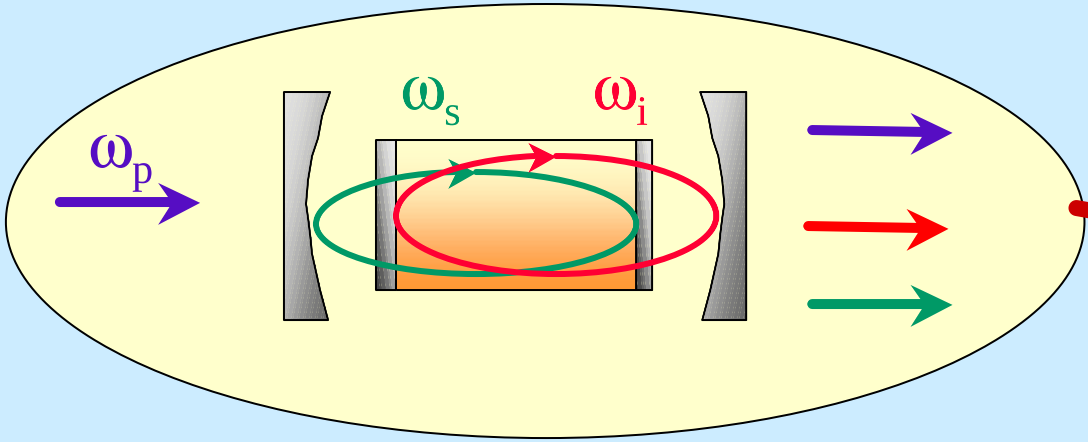
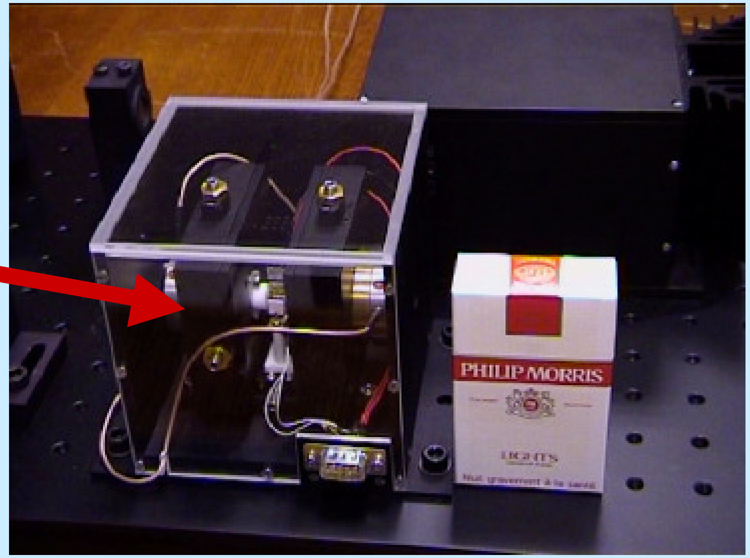
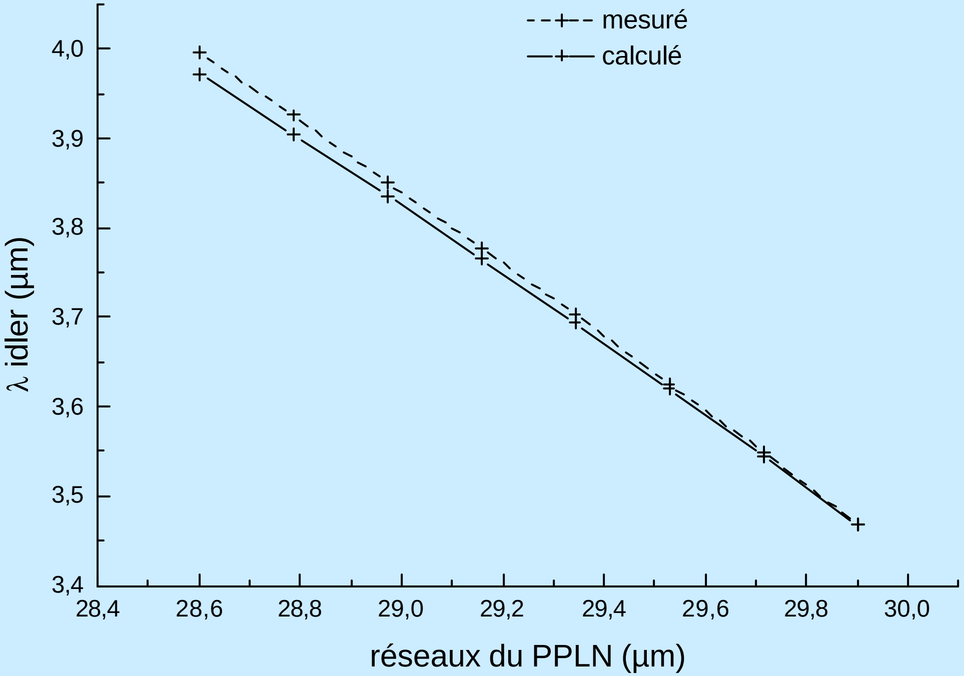
DMPH

Semi-monolithic dual cavity mid-IR DROPO







Performances :

f ~ 15 kHz

E = 1 µJ/pulse

λi tunable 3 to 4,5 µm

Threshold ~ 4 µJ/pulse

single frequency (~ 200 MHz)

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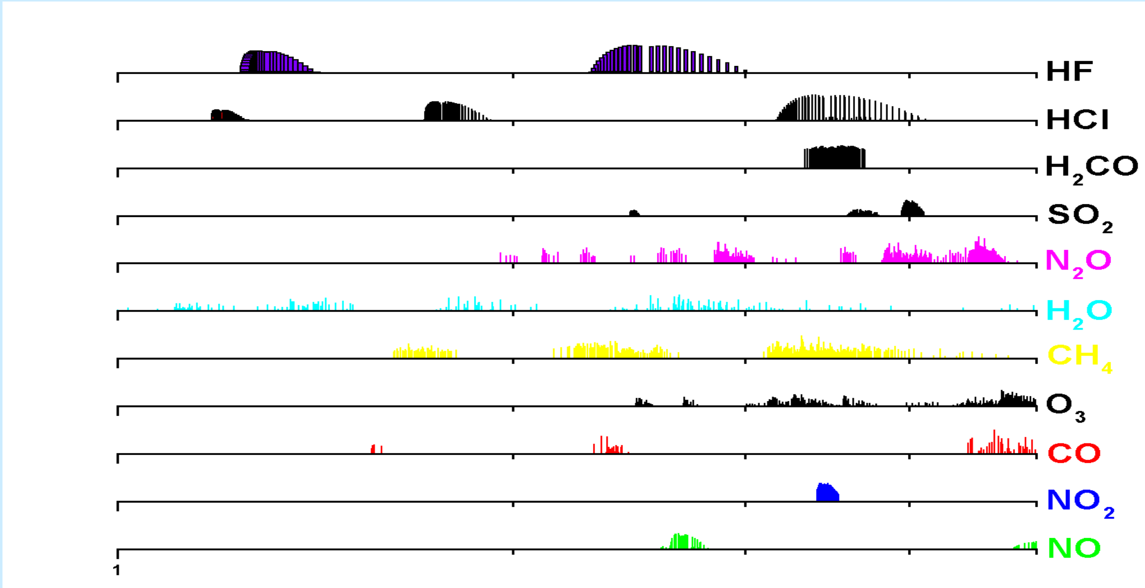
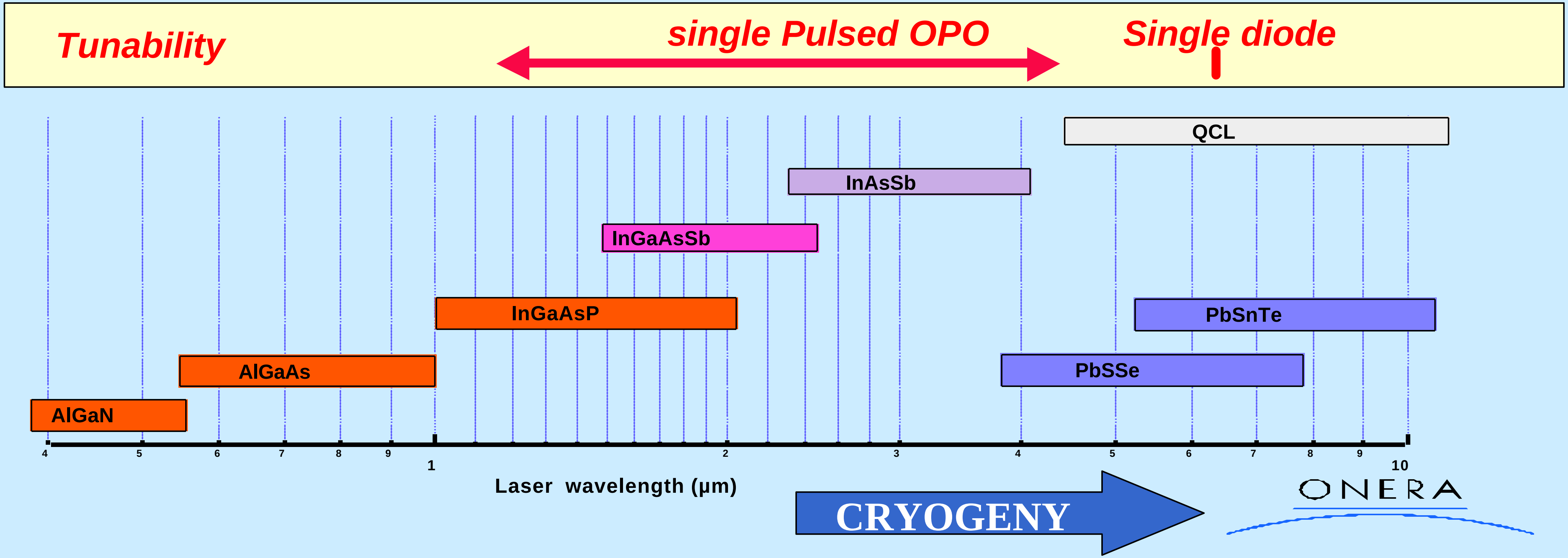
Lefebvre, Rosencher, Ribet,Drag JOSA 2000, OL 2002

Diodes laser

vs

OPO





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SEMICONDUCTORS

- 0.45 µm < λ_{cutoff} < 20 µm (0.05 eV < E_{gap} < 3 eV)

- High nonlinear peformance (band theory) :

Second Fermi Golden Rule

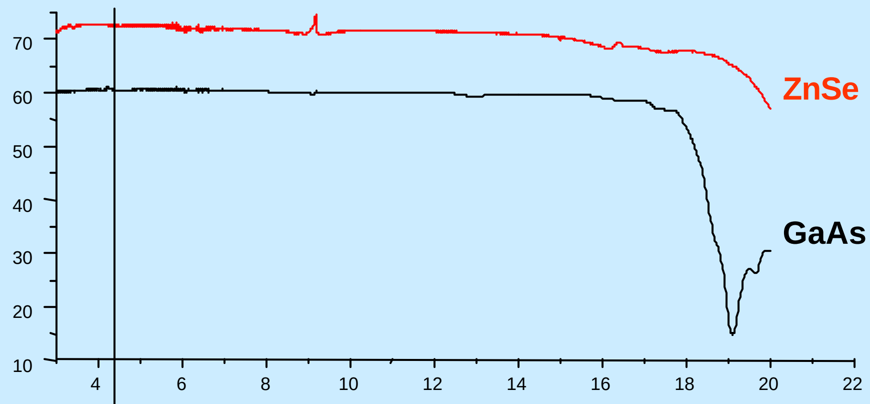
$$P_{NLO} \propto \frac{d^2}{n^3} \propto \frac{E_{gap}^{-4}}{E_{gap}^{-3}} \propto \lambda_{cutoff}$$

Harmonic oscillator

- Large transparency region

- Low cost

- Mature technology III-V



- Isotropic materials ⇒ NO possible phase matching scenario

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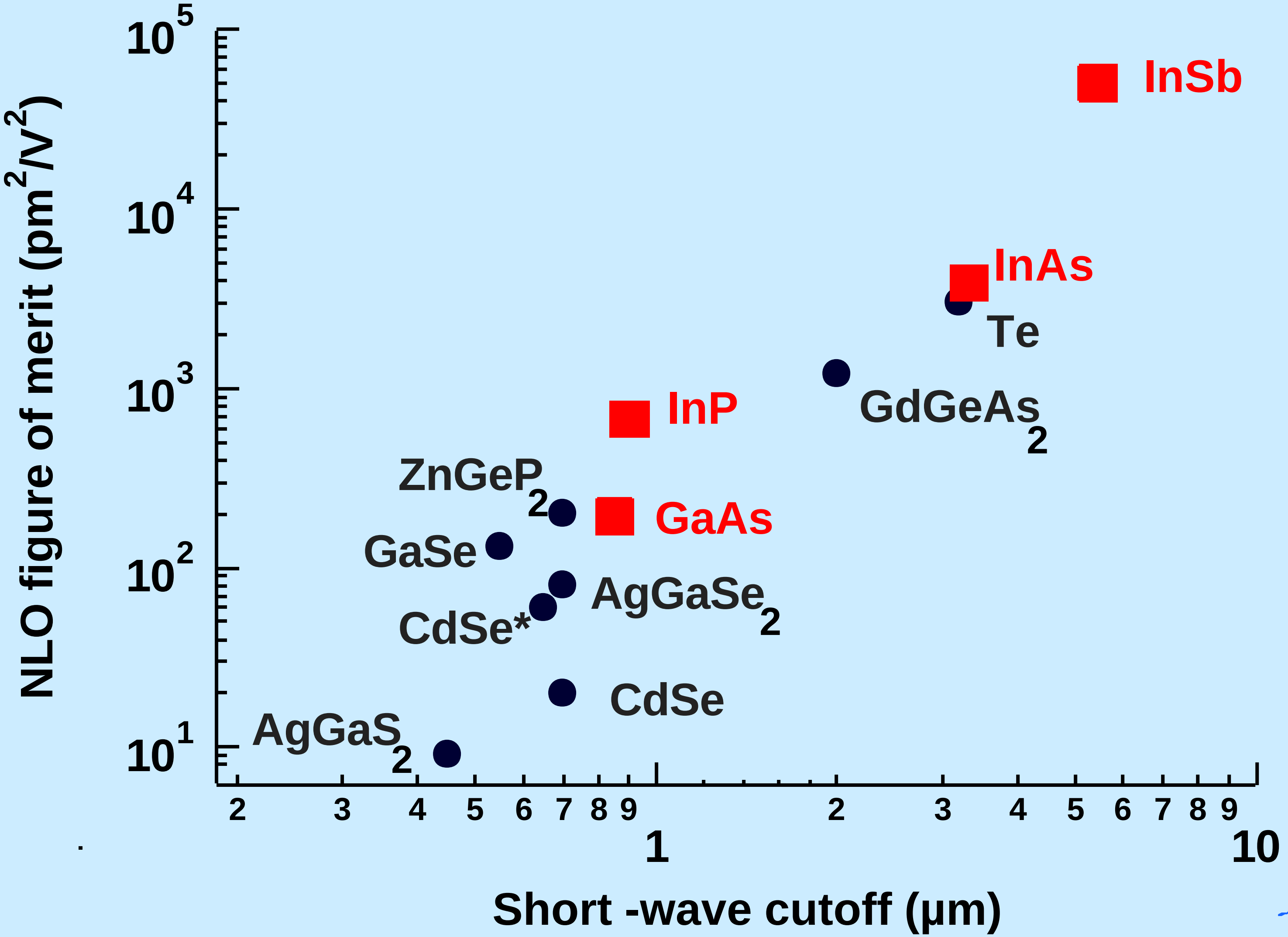
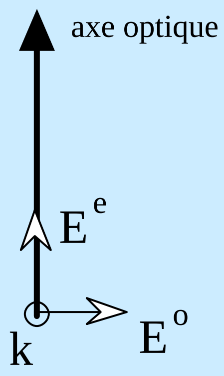
Figure de mérite des semiconducteurs

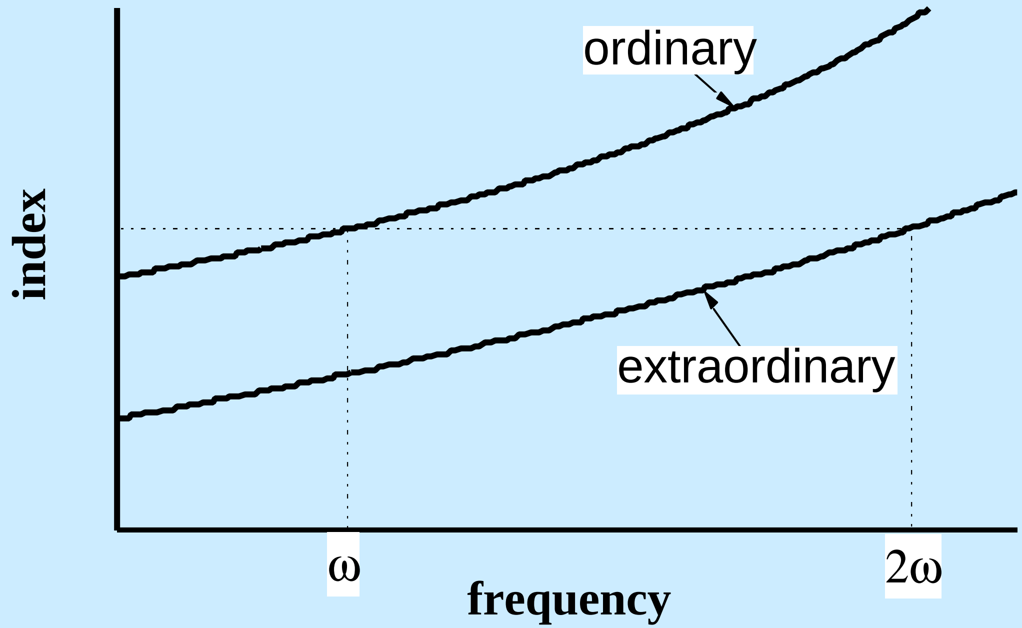
$$\frac{d^2}{n^3}$$



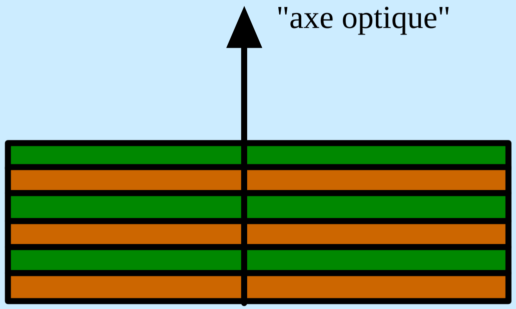
PHASE MATCHING BY ARTIFICIAL BIREFRINGENCE

cristaux biréfringents: (ex. KTP)





biréfringence de forme: (ex. GaAs/AlAs)



$$n_o(w) = n_e(2w) \Rightarrow \textit{accord de phase}$$

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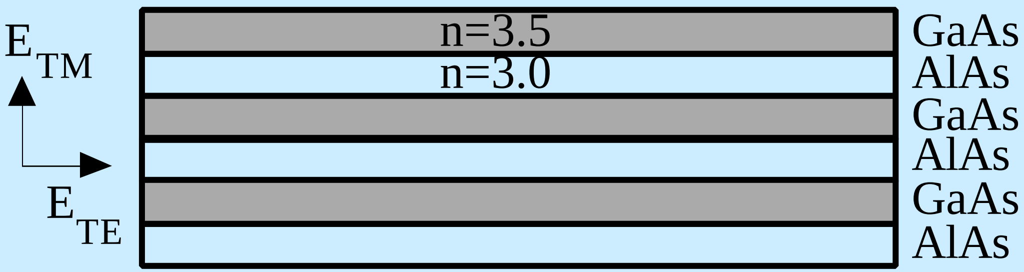
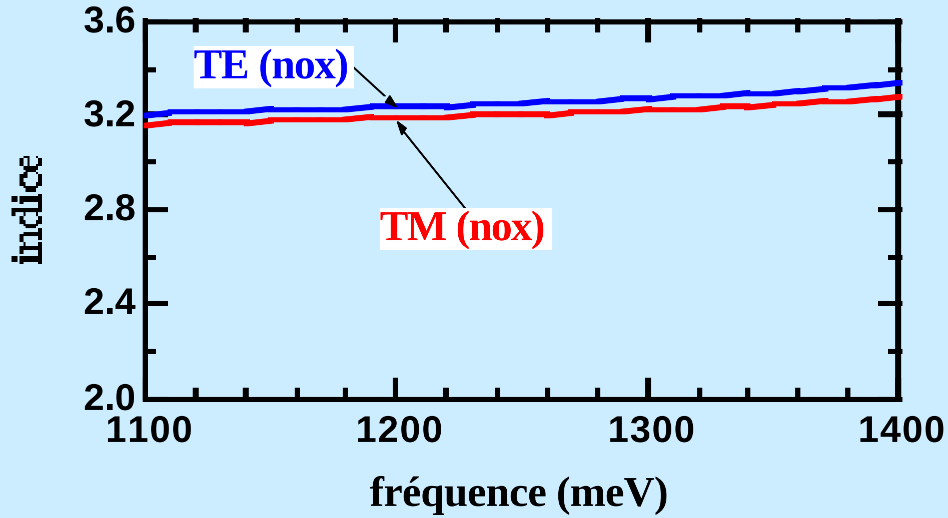
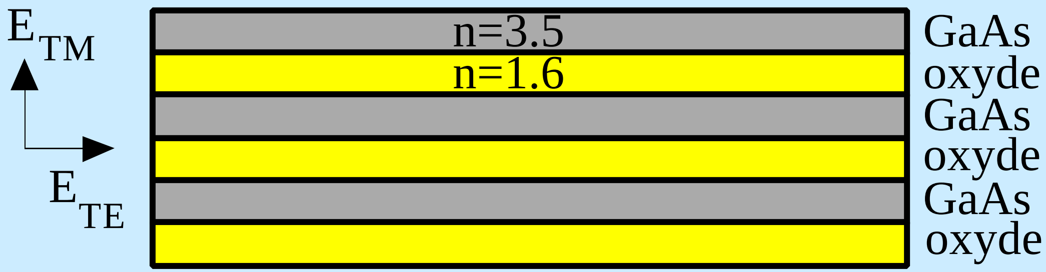
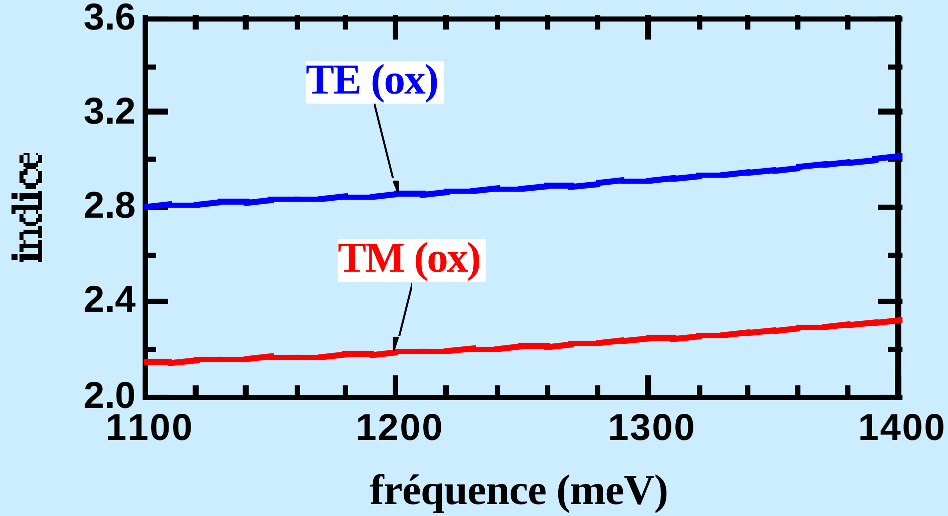
GIANT BIREFRINGENCE IN GaAs/AlOx heterostructures









$$E_{TE}(1) = E_{TE}(2)$$

$$n_1^2 \; E_{TM}(1) = n_2^2 \; E_{TM}(2)$$

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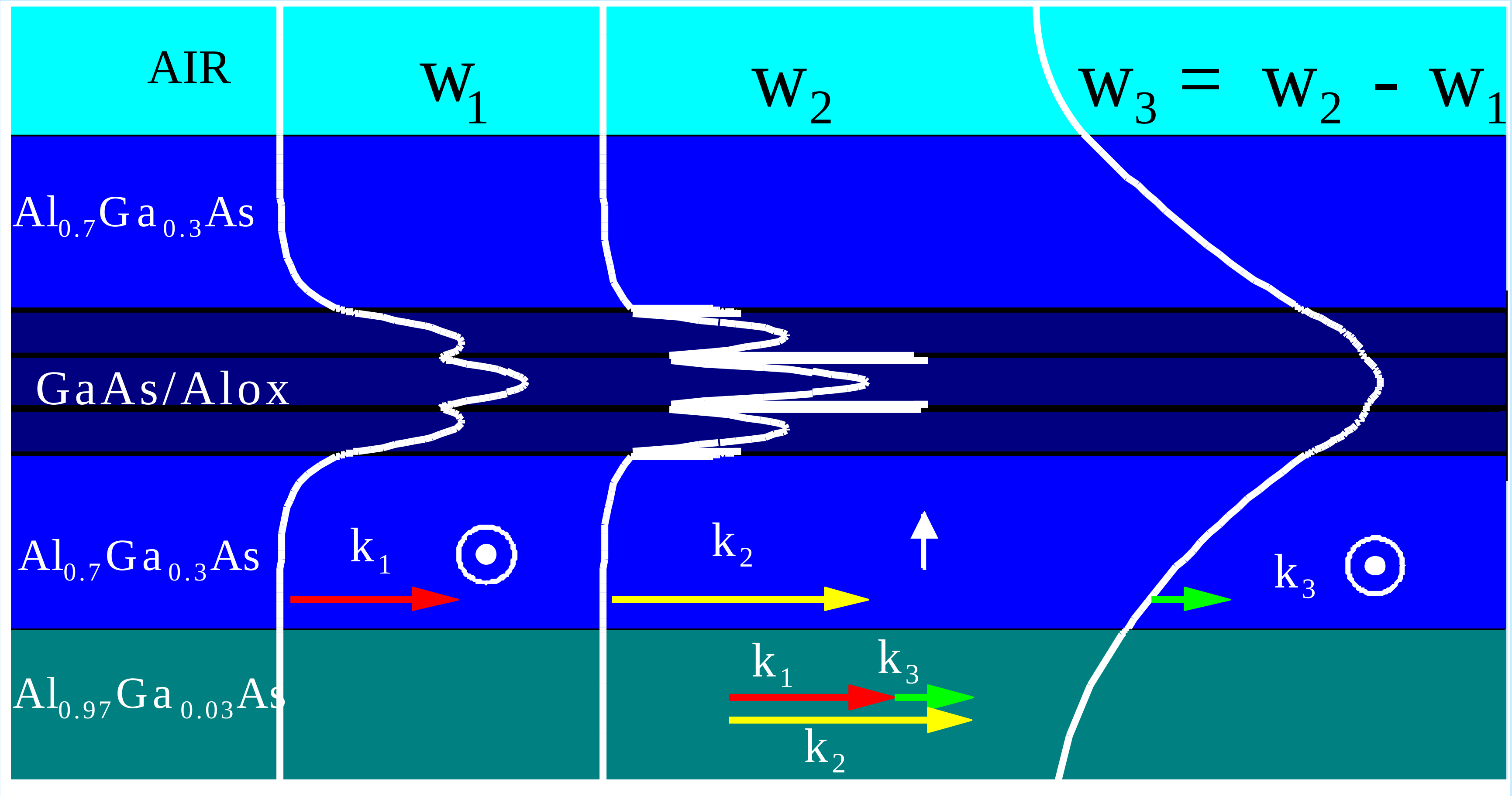
AIR
w_1
w_2
$w_3 = w_2 - w_1$
$Al_{0.7}Ga_{0.3}As$
GaAs/Alox
$Al_{0.7}Ga_{0.3}As$
k_1
k_2
k_3
$Al_{0.97}Ga_{0.03}As$
k_1
k_3
k_2

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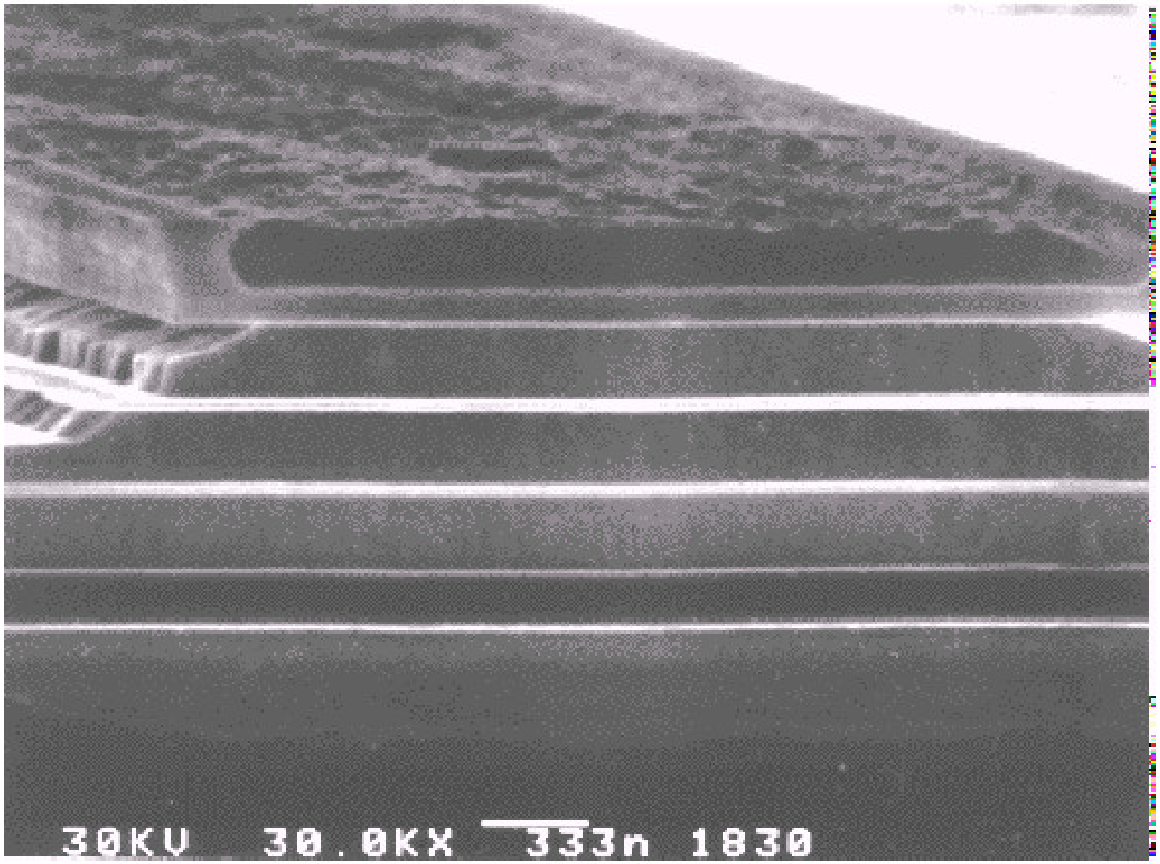
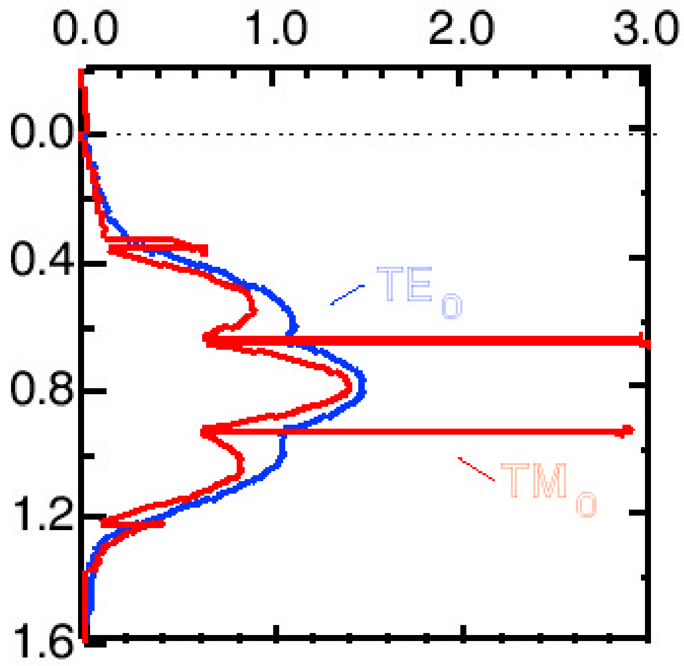
SAMPLE AND ELECTRIC FIELD DISTRIBUTION





OPTIMISATION DE $\int E_1(z)E_2(z)E_3(z)\,dz$

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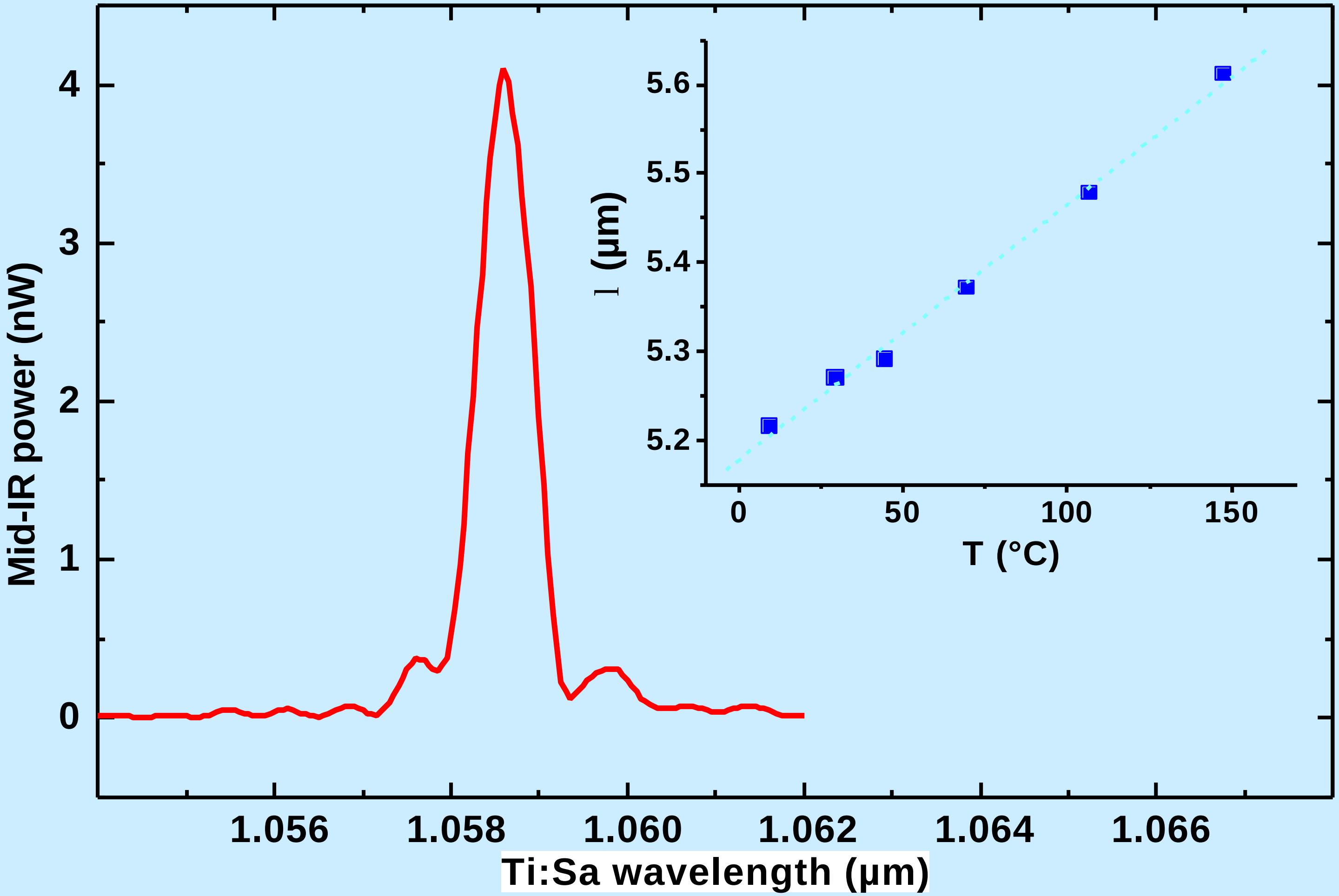
IR OUTPUT AND TUNABILITY



Fiore, Berger, Rosencher, Nagle Nature 1998

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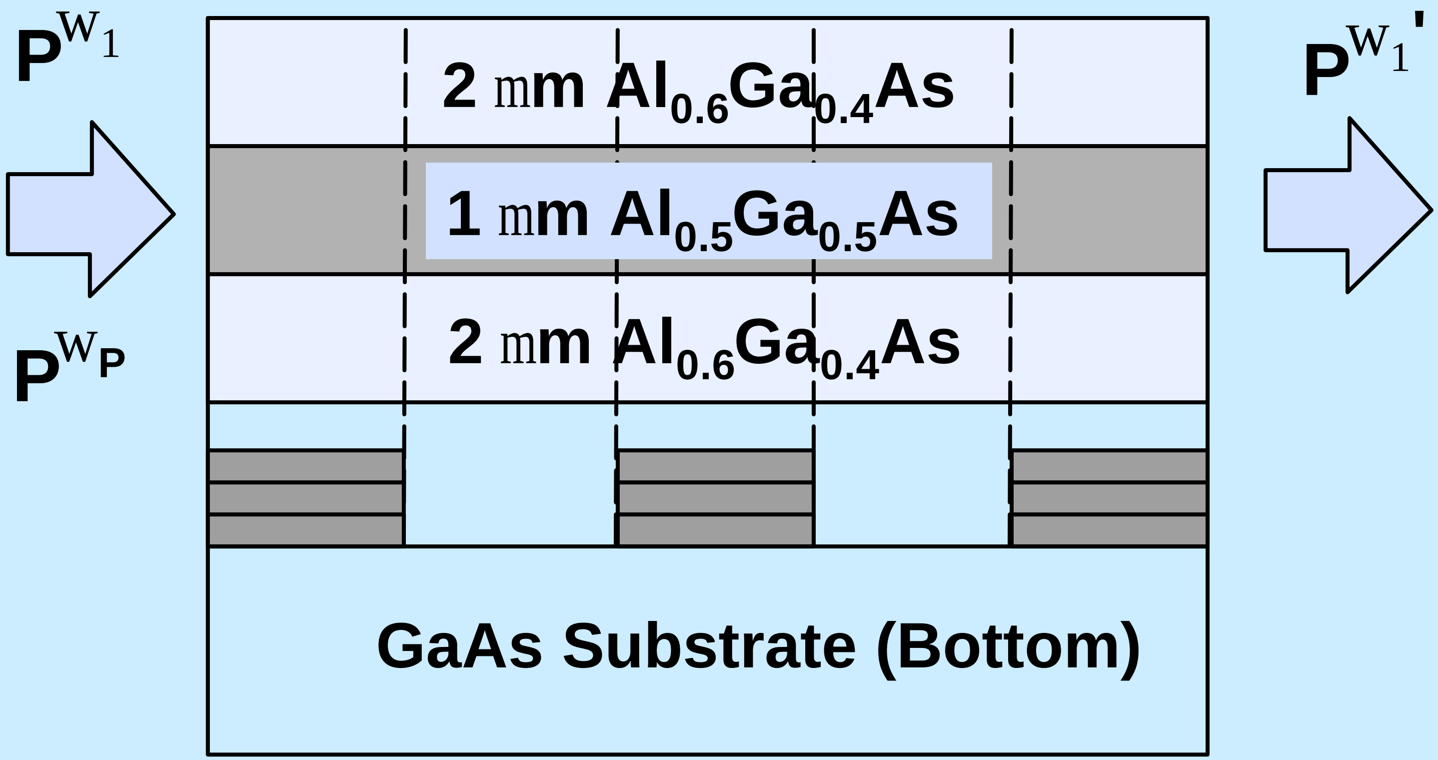
QUASI PHASE MATCHING IN GaAs/AlGaAs waveguide: the patterned growth method



MBE: Ben Yoo ,APL (1997)
MOCVD : M. Fejer and B. Gérard, APL (2000)

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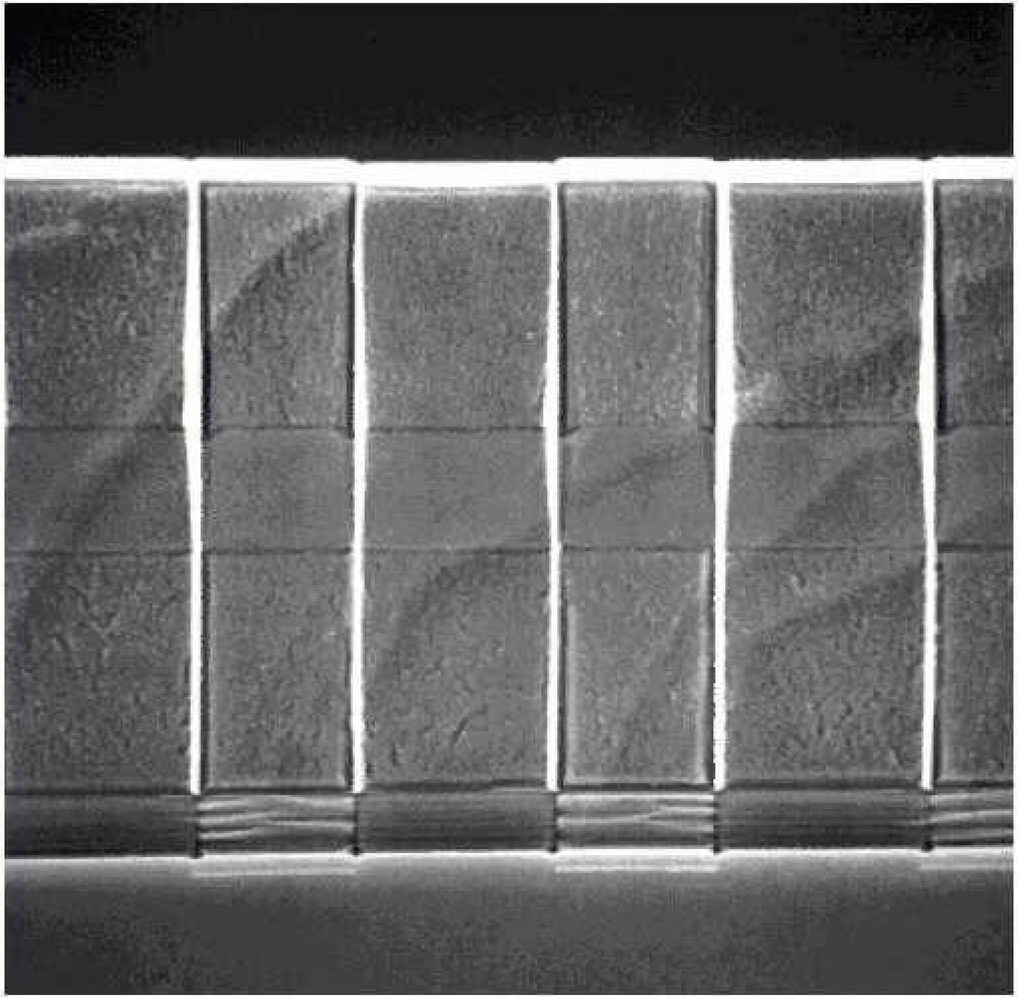

3 mm

MBE: Ben Yoo ,APL (1997)

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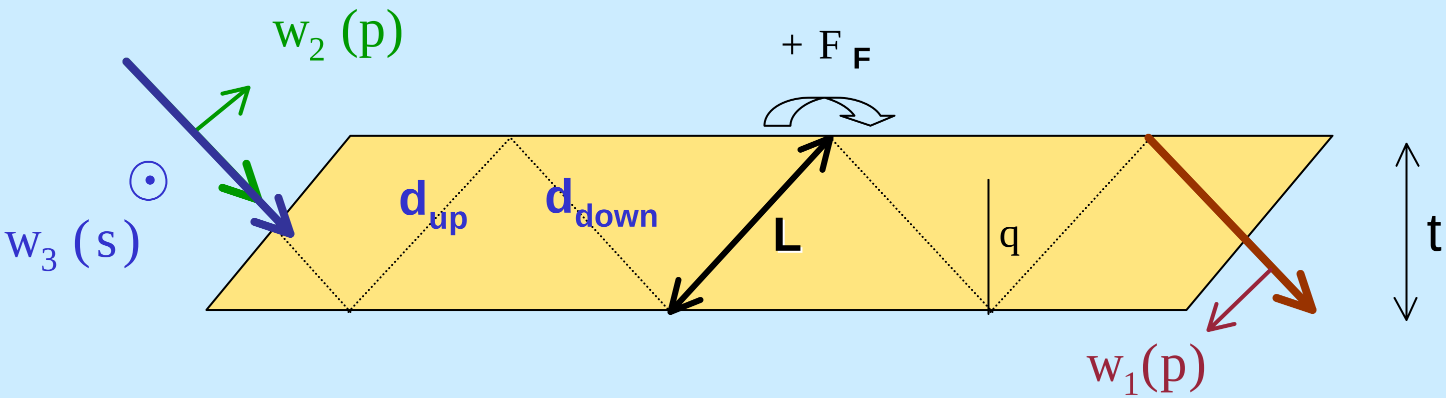
Quasi Phase Matching by Total Internal Reflexion * taking into account Fresnel Birefringence



$$d f_{tot} = D\mathbf{k.L} + F_{F} + \begin{cases} 0 & \textbf{if } d_{up} \,.\, d_{down} > 0 \\ p & \textbf{if } d_{up} \,.\, d_{down} < 0 \end{cases}$$

*Armstrong et al., Phys. Rev. **127**, 1918-1939 (1962)

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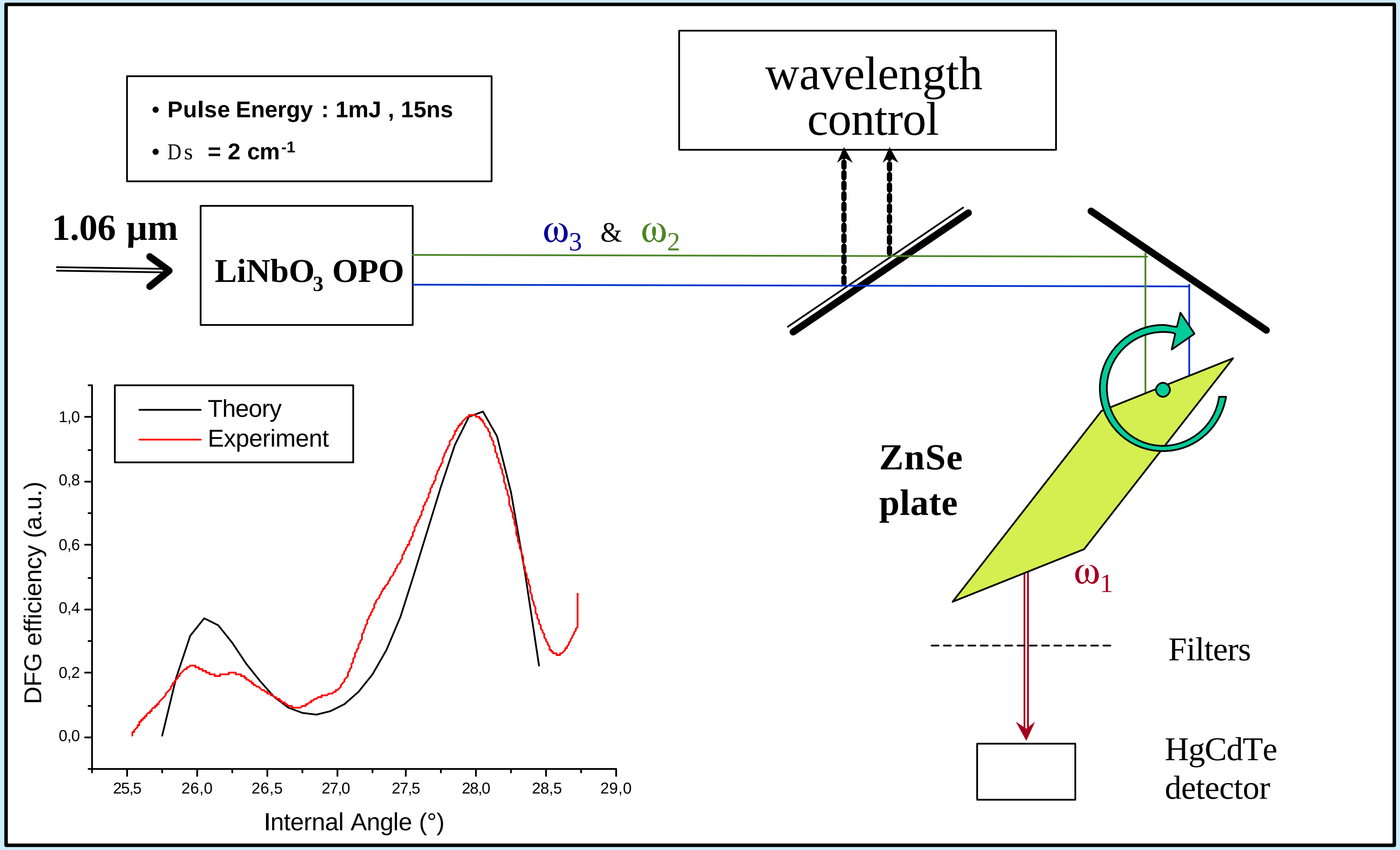
Fresnel phase matching Configuration :
experimental set-up



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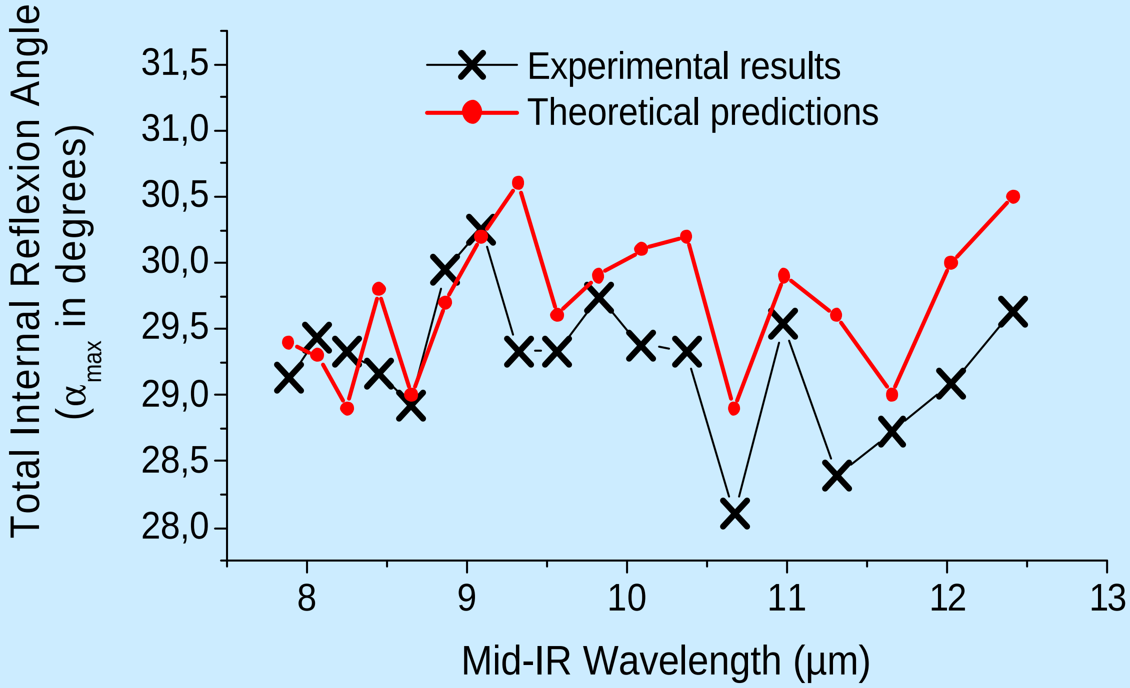
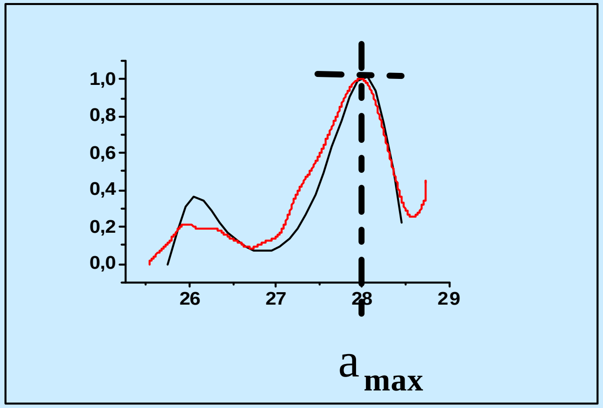
Tuning behaviour of Fresnel phase matching





Haidar, Kupecek, Rosencher APL 2002, 2003

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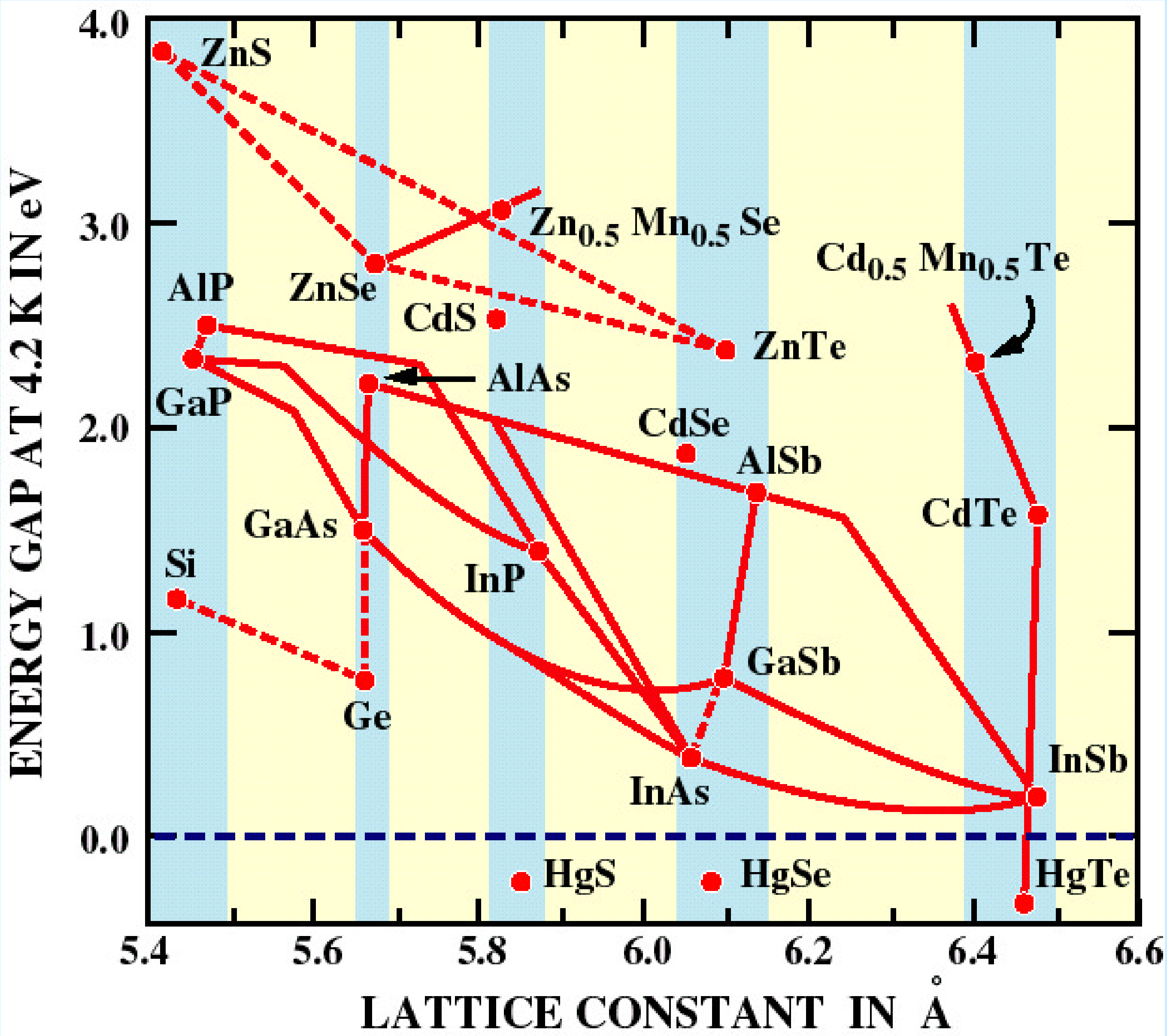
Familles de semiconducteurs



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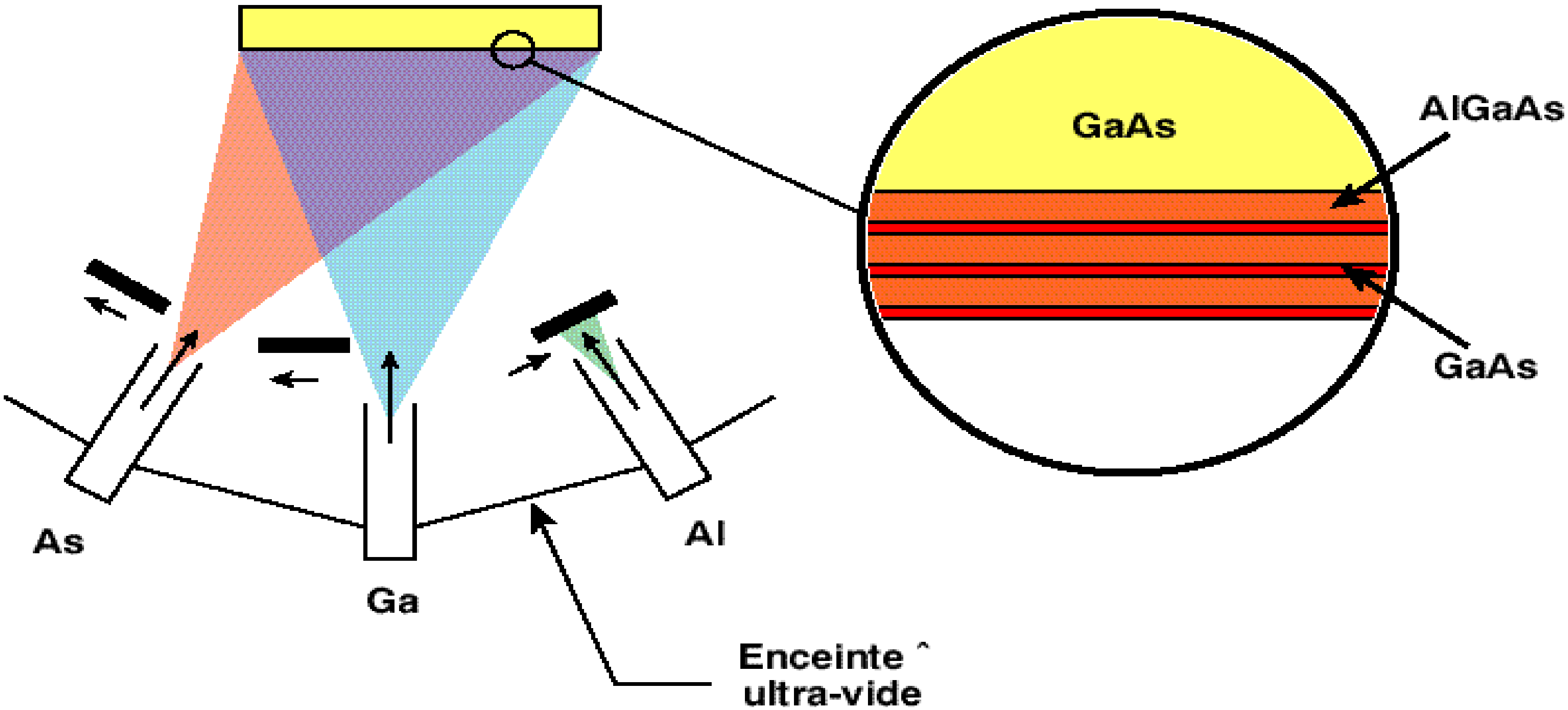
EPITAXIE PAR JETS MOLECULAIRES



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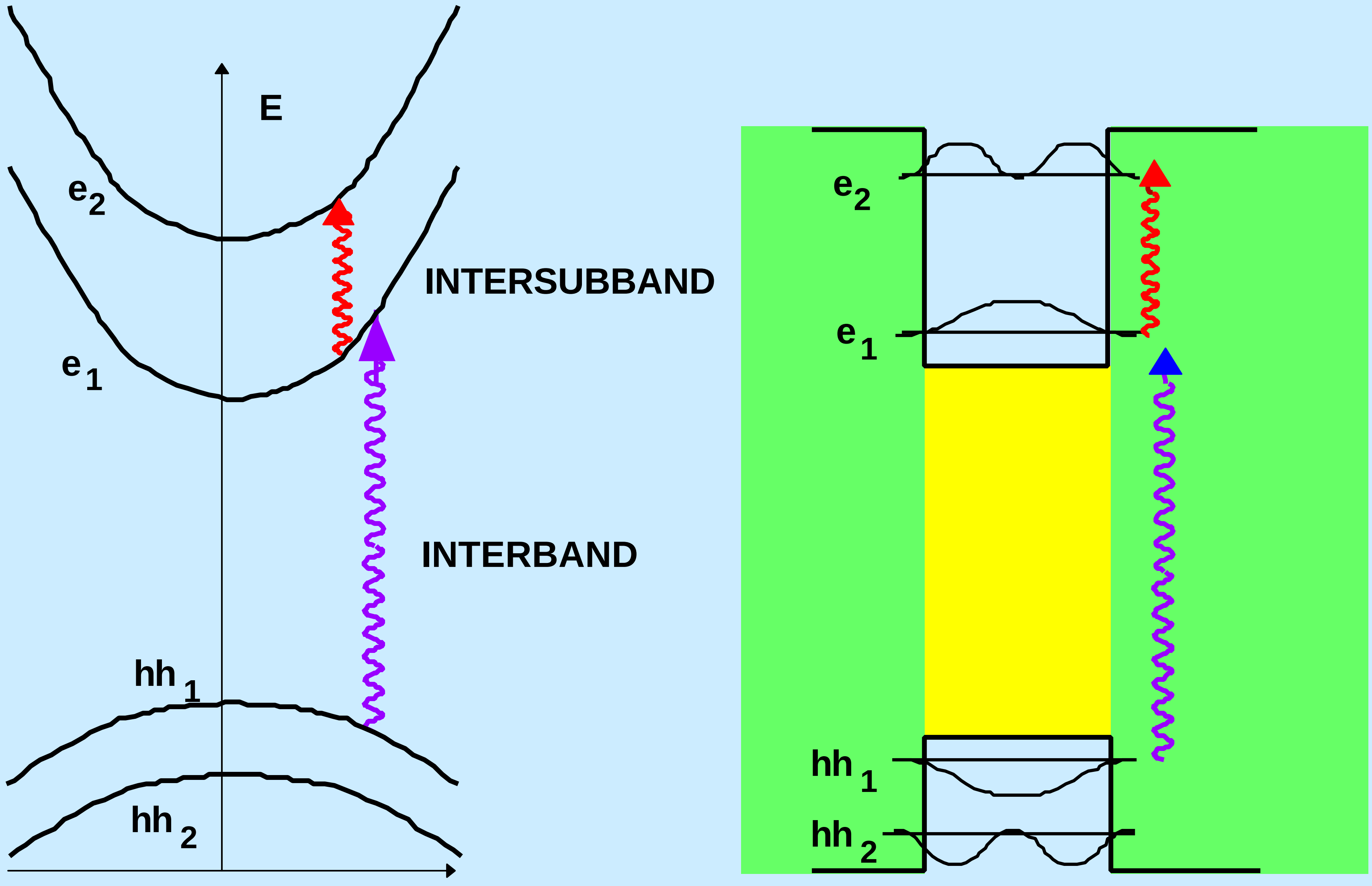

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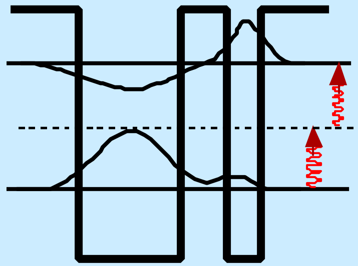
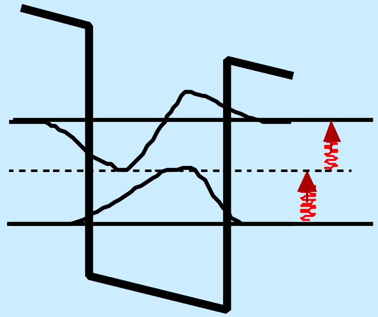
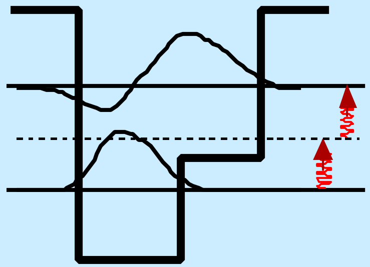
Différentes structures asymétriques



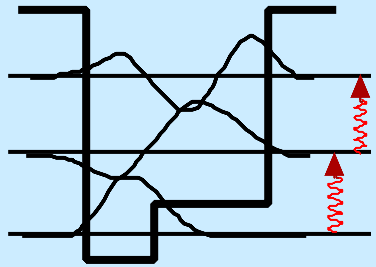
(A)



(B)



(C)



(D)

ORIGIN OF GIANT OPTICAL SUSCEPTIBILITY

Second Fermi golden rule :

$$c^{(2)} = \frac{q^3 n_s}{e_0 \hbar^2} m_{31} \frac{m_{12}}{total\ energy\ mismatch\ 1 ® 2} \frac{m_{23}}{total\ energy\ mismatch\ 2 ® 3}$$

Two effects in QWs :

$$c^{(2)} » \frac{q^3 n_s}{e_0 \hbar^2} \frac{m_{12} m_{23} m_{31}}{(w - w_{12} - ig)(2w - 2w_{12} - ig)}$$

$\frac{1}{m_c^{3/2}}$ effective mass

$\frac{1}{dw^2}$ double resonnance

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Approche quantique de l'Optique Non Linéaire:1

r **matrice densité du système quantique** $r \equiv \sum_i p_i \left| j_i \right\rangle \left\langle j_i \right|$

p_i **probabilité statistique que le système soit dans un état** j_i

$$\left\langle \overline{A} \right\rangle = Tr\left(r\, A \right)$$

r_{ii} **population moyenne de l'état i**

r_{ij} **cohérence entre les états i et j**

$$\frac{\partial r_{ij}}{\partial t} = \frac{1}{i\hbar}\left[H_0 - q\,z\,E(t), r\right]_{i,j} - G_{i,j}\left(r - r^{(0)}\right)_{i,j}$$

Exemple: valeur moyenne de la polarisation

$$P(t) = Tr\left(r\, q\, \hat{z} \right)$$

Approche quantique de l'Optique Non Linéaire:2

Approche perturbative

$$r(t) = \sum_n r^n(t)$$

avec

$$\frac{\partial r_{i,j}^{n+1}}{\partial t} = \frac{1}{i\hbar}\left\{\left[H_0, r^{n+1}\right]_{i,j} - i\hbar G_{i,j}\, r_{i,j}^{n+1}\right\} - \frac{1}{i\hbar}\left[q\,\hat{z}\,E(t), r^n\right]_{i,j}$$

La polarisation est maintenant la somme de contribution d'ordres croissants

$$P^n(t) = Tr\left(r^n\, q\,\hat{z}\right)$$

avec

$$r^n(t) = r^n(w)\,e^{inwt} + cc$$

aux deux premiers ordres

$$P(t) = \underbrace{e_0\, c^{(1)} E\, e^{iwt}}_{\text{Optique linéaire}} + \underbrace{e_0\, c^{(2)} E^2\, e^{i2wt}}_{\text{GSH}} + \underbrace{e_0\, c_r \left|E\right|^2}_{\text{Rectification optique}}$$

Optique linéaire GSH Rectification optique

Approche quantique de l'Optique Non Linéaire:3

Relation de récurrence

$$r_{i,j}^{n+1}(w) = \frac{q\left[\hat{z}, r^{n}\right]_{i,j}}{\hbar\left[(n+1)w + w_{i,j} - iG_{i,j}\right]}E$$

Aux deux premiers ordres

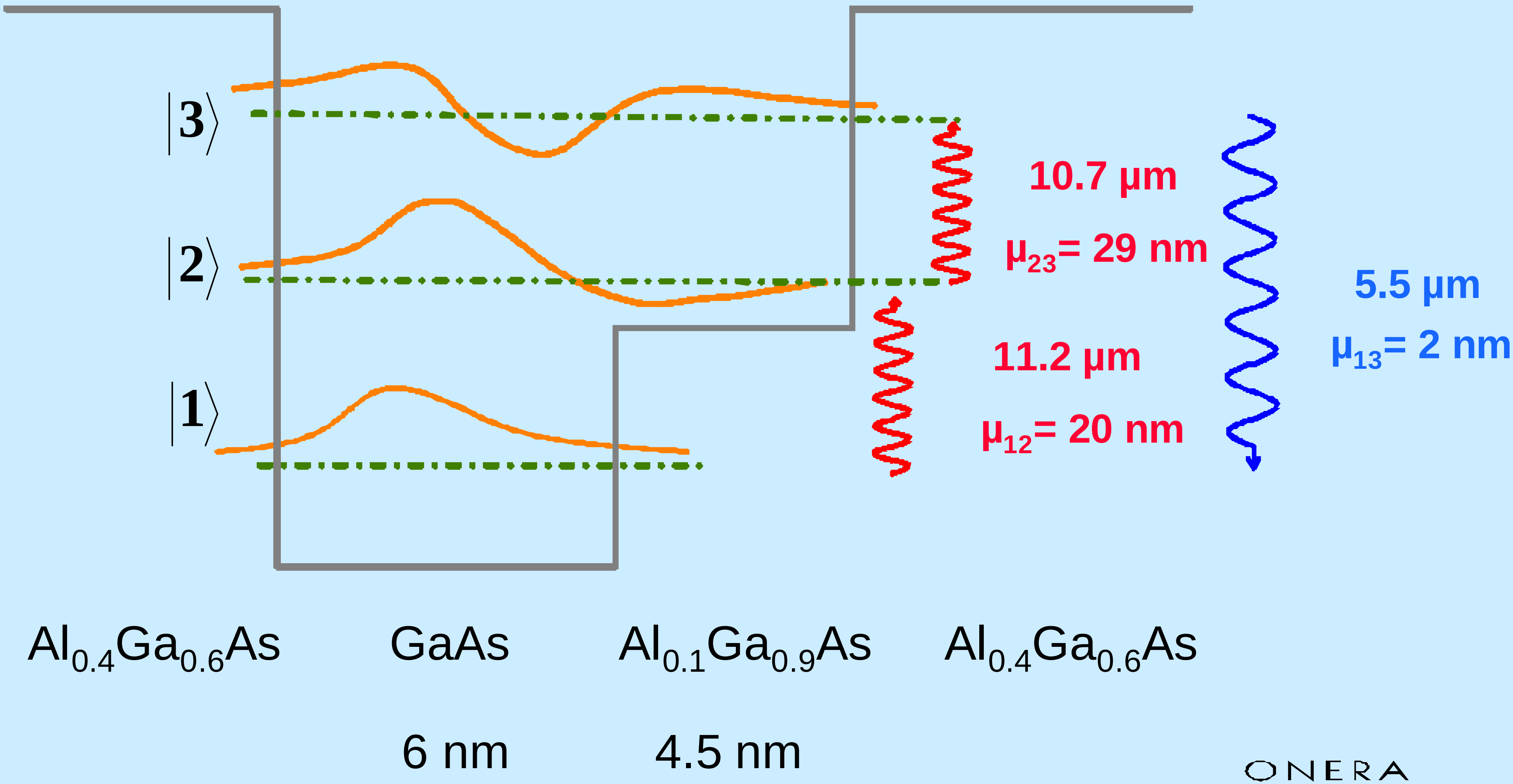
$$\begin{cases} r_{i,j}^{1}(w) = \dfrac{q\, z_{i,j}\left(n_j - n_i\right)}{\hbar\left[w + w_{i,j} - iG_{i,j}\right]}E \\[2ex] r_{i,j}^{2}(w) = \dfrac{1}{\hbar\left[2w + w_{i,j} - iG_{i,j}\right]}\left[q\,\hat{z}, r^{1}\right]_{i,j}E \end{cases}$$

$$c^{(2)} = \frac{q^3}{e_0\hbar^2}\sum_{i}\sum_{i}\frac{1}{(2w + w_{ki}) - i\,G_{ki}}$$

$$\sum_{l} m_{ik} m_{kl} m_{li}\left[\frac{n_i - n_l}{(w + w_{li}) - i\,G_{li}} - \frac{n_l - n_k}{(w + w_{kl}) - i\,G_{kl}}\right]$$

Purement quantique

STRUCTURE QUANTIQUE ASYMETRIQUE: «LA» FORME OPTIMALE



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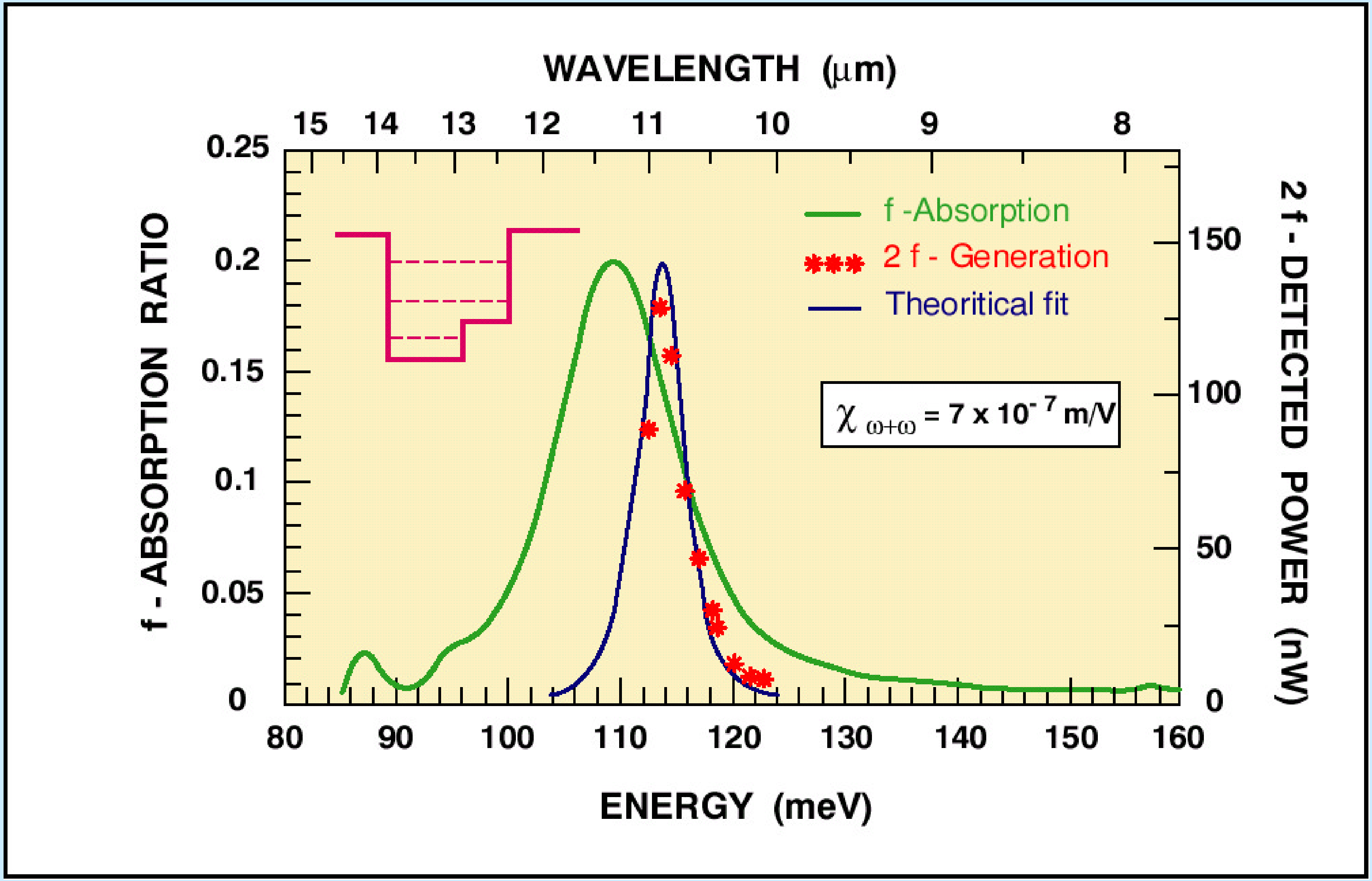

Rosencher et Bois, Science 1996

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CONCLUSIONS

- Semiconductors: already very useful parametric sources in the 6 – 13 µm range
  soon parametric oscillations

	pros	cons
QPM by molecular bonding	• No growth • possibility of complex structures	•Large tunablility only from the MIR •Time consuming, manual
QPM by patterned growth	• Large tunablility • mass production	•Extreme technological difficulties
Fresnel phase matching	• no technology • parametric florescence • NR-QPM: high tunability, tolerance	• complex optical system • highly demanding in roughness control
Microcavity OPO	• integration potential • simple micro-device	• low tunability
Artificial birefringence in waveguide	•mass production • integration potential	•Extreme technological difficulties

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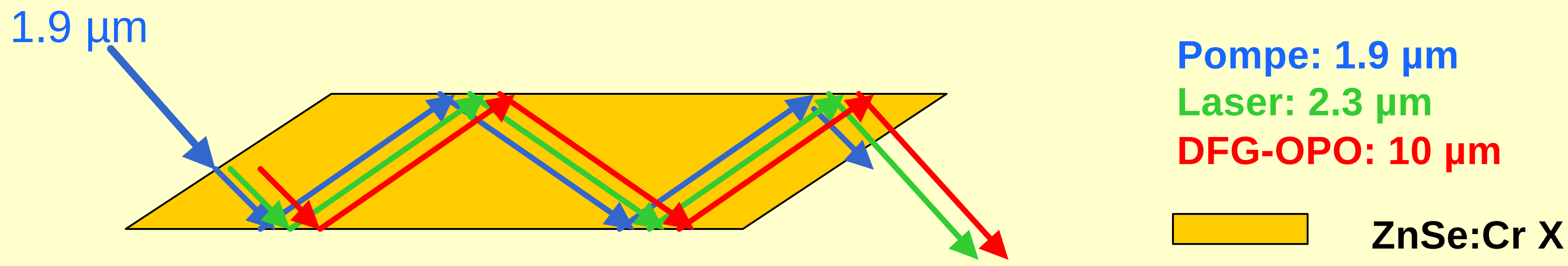
Future work

Sol 1: auto-OPO accordé en biréfringence de Fresnel



Sol 2: auto-OPO quasi-accordé en phase

Sol 3: passer de la DFG à l'OPO