

Acumulação coerente da excitação de um sistema de três níveis por um trem de pulsos ultra-curtos

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Introdução

Estudo teórico da interação entre um trem de pulsos de um laser de femtosegundos e um sistema de 3 níveis do tipo Lambda, Vee e Cascata, no regime de acumulação coerente. Mostraremos que as coerências dependem fortemente do tipo de sistema, da área de cada pulso e da taxa de repetição do laser.

Roteiro:



Breve resumo dos aspectos importantes de um trem de pulsos de femtosegundos e da sua interação com um sistema atômico de 2 níveis.



Interação entre um pulso de femtosegundos e um sistema de 3 níveis.

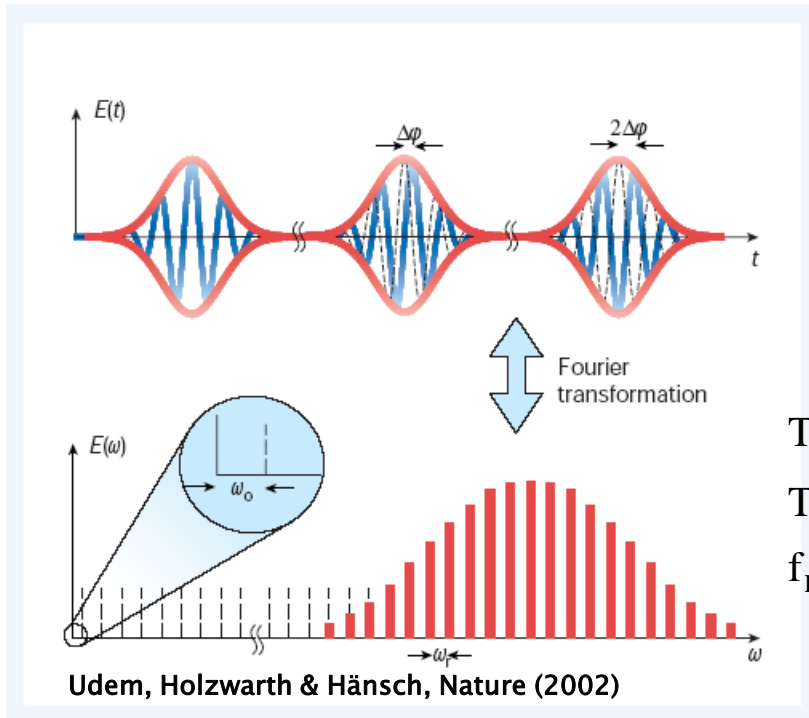


Interação entre um trem de pulsos de femtosegundos e um sistema de 3 níveis.



Perspectivas.

O trem de pulsos



$$f_n = f_0 + n f_R$$

$$f_R = 1/T_R$$

$$f_0 = (\Delta\phi / 2\pi) f_R$$

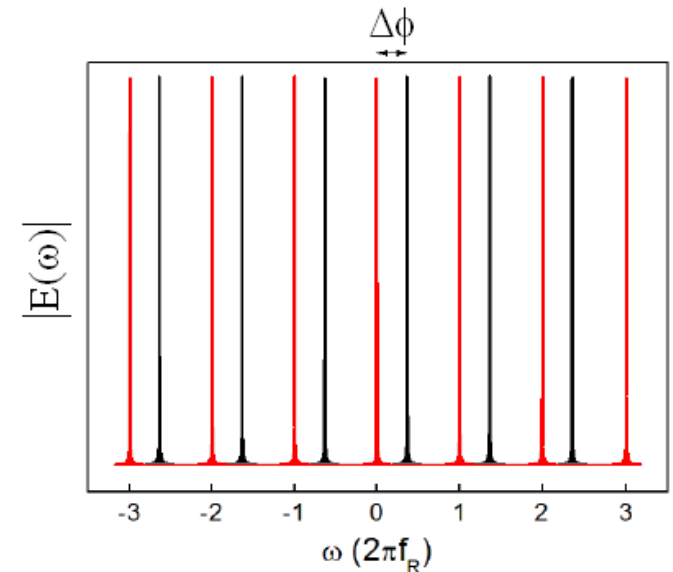
Heichert, Holzwarth, Udem & Hänsch, Opt. Commun. (1999)

Nesse seminário:

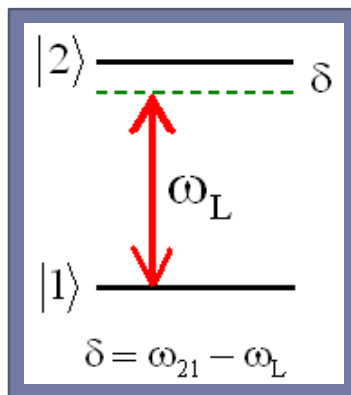
$$\Delta\phi = 0 \Rightarrow f_0 = 0$$

$$E(t) = E_0 \sum_{n=0}^N \text{sech}\left(\frac{t - nT_R}{T_p}\right) e^{in\phi} e^{i\omega_L t} + \text{c.c}$$

$$E(t) = E_0(t) e^{i\omega_L t} + \text{c.c}$$



Sistema de 2 níveis



Equações de Bloch

$$\frac{\partial \rho_{11}}{\partial t} = -i\Omega_0(t)/2\sigma_{12} + c.c$$

$$\frac{\partial \rho_{22}}{\partial t} = i\Omega_0(t)/2\sigma_{12} + c.c$$

$$\frac{\partial \sigma_{12}}{\partial t} = i\delta\sigma_{12} + i\Omega_0(t)/2(\rho_{22} - \rho_{11})$$

Allen and Eberly, (Dover, 1987)

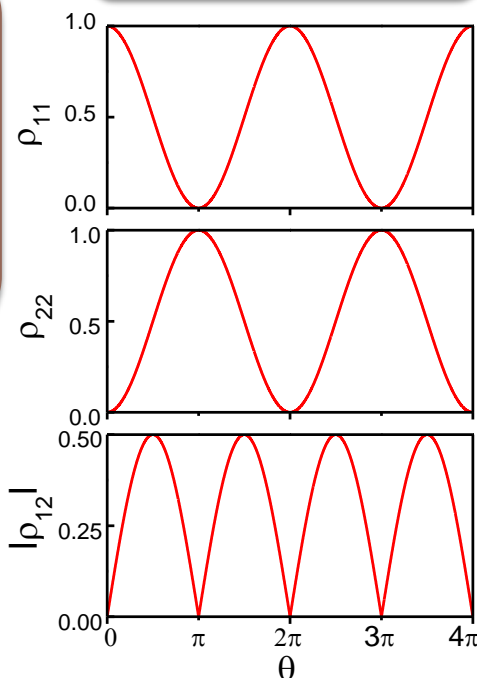
Frequência de Rabi

$$\Omega_0(t) = \frac{2\mu_{12}E_0(t)}{\hbar}$$

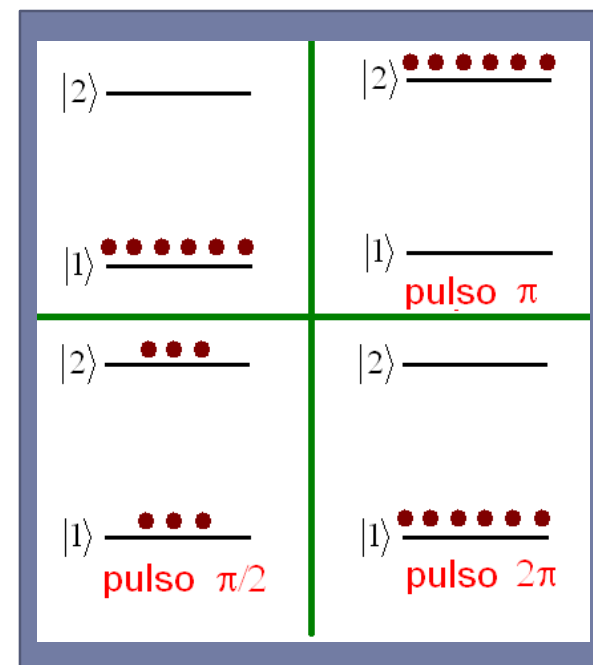
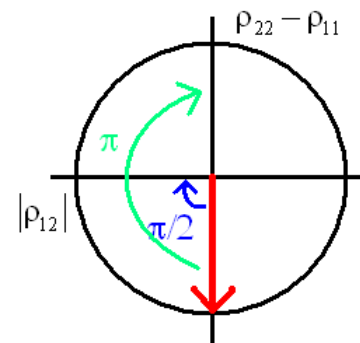
Um único pulso:

$$\begin{cases} \rho_{11}(t=0) = 1 \\ \rho_{22}(t=0) = 0 \\ \sigma_{12}(t=0) = 0 \end{cases} \quad \delta \ll \Delta\omega_{fs}$$

$$\theta = \int_{-\infty}^{\infty} \Omega_0(t) dt$$



Esfera de Bloch



Sistema de 2 níveis + trem de pulsos

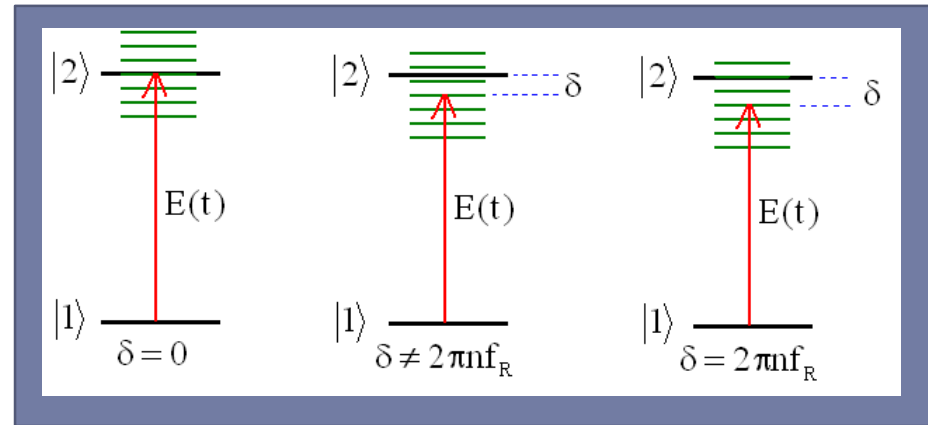
Efeitos de um trem de pulsos:

$$T_{12} = 2T_{22} = 50 \text{ ns}$$

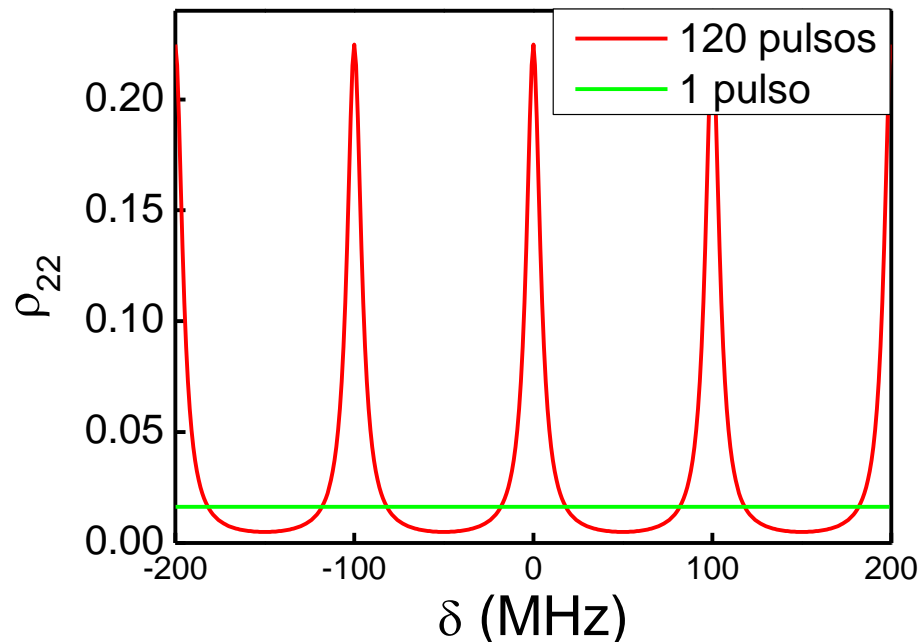
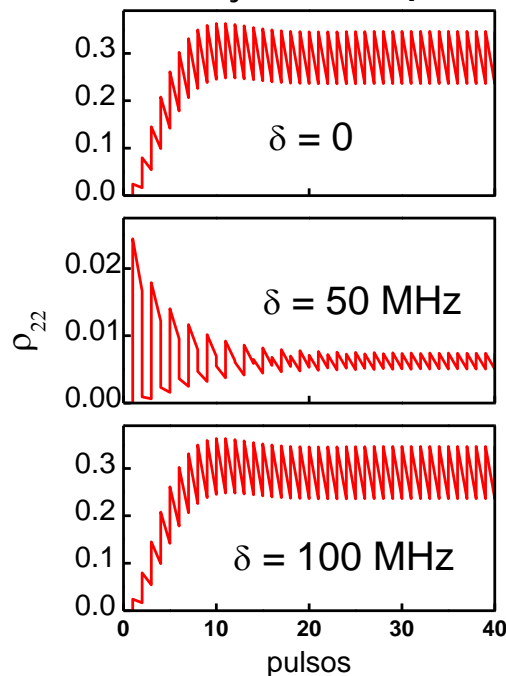
$$T_R = 10 \text{ ns} \Rightarrow f_R = 100 \text{ MHz}$$

$$\theta = \pi / 10$$

$$T_p = 150 \text{ fs} \Rightarrow \Delta\omega_L \sim 6 \text{ THz}$$

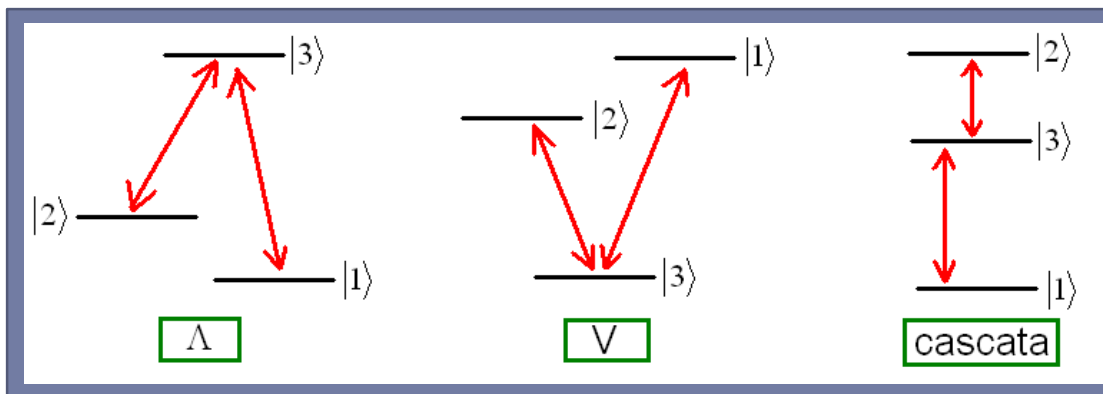


Evolução temporal:

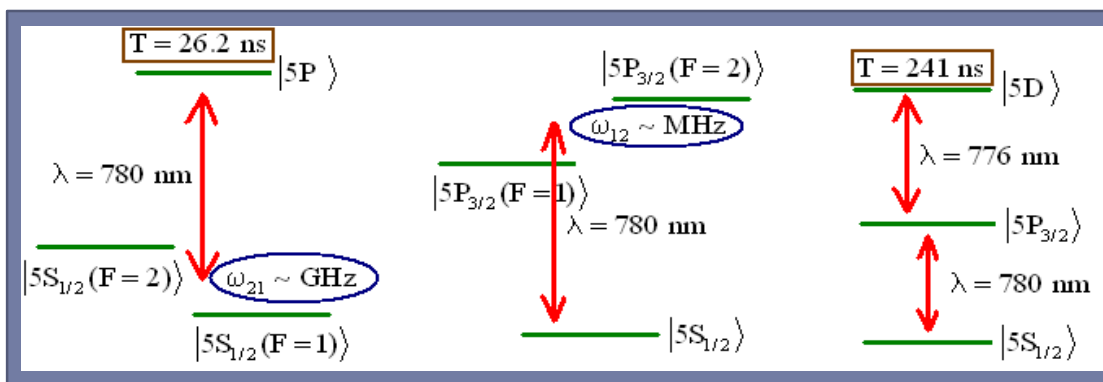


Felinto, Bosco, Acioli, Vianna, Opt. Commun. (2003)

SISTEMAS DE 3 NÍVEIS



A transição $|1\rangle \rightarrow |2\rangle$ por 1 fóton é proibida.

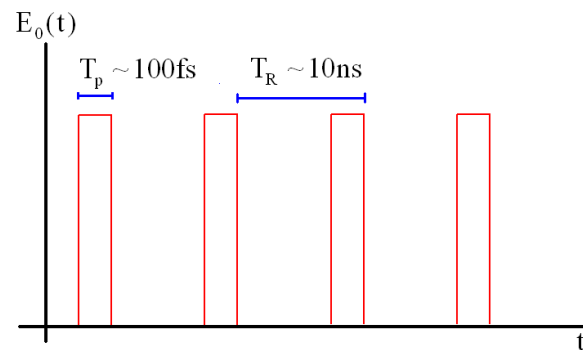


Formalismo da matriz densidade

$$\frac{\partial \hat{\rho}}{\partial t} = -\frac{i}{\hbar} [\hat{H}, \hat{\rho}]$$

$$\hat{H} = \sum_{k=1}^3 |k\rangle \langle k| - \hat{\mu} \cdot \vec{E}$$

Interação com pulsos quadrados



Aproximações: envelope-lento, onda-girante

SISTEMAS DE 3 NÍVEIS

Equações de Bloch – um único pulso:

$$\frac{\partial \rho_{11}}{\partial t} = -i \frac{\Omega_{13}}{2} \sigma_{13} + \text{c.c.}$$

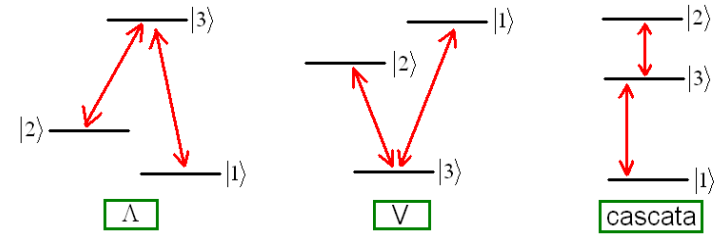
$$\frac{\partial \rho_{22}}{\partial t} = -i \frac{\Omega_{23}}{2} \sigma_{23} + \text{c.c.}$$

$$\frac{\partial \rho_{33}}{\partial t} = i \frac{\Omega_{13}}{2} \sigma_{13} + \text{c.c.} + i \frac{\Omega_{23}}{2} \sigma_{23} + \text{c.c.}$$

$$\frac{\partial \sigma_{12}}{\partial t} = i \left\{ \begin{array}{c} 2(\Delta - \delta) \\ \delta_c \end{array} \right\} \sigma_{12} + i \frac{\Omega_{13}}{2} \sigma_{32} - i \frac{\Omega_{23}}{2} \sigma_{13}$$

$$\frac{\partial \sigma_{13}}{\partial t} = i \left\{ \begin{array}{c} \Delta \\ \Delta \end{array} \right\} \sigma_{13} + i \frac{\Omega_{13}}{2} (\rho_{33} - \rho_{11}) - i \frac{\Omega_{23}}{2} \sigma_{12}$$

$$\frac{\partial \sigma_{23}}{\partial t} = i \left\{ \begin{array}{c} 2\delta - \Delta \\ \delta_c - \Delta \end{array} \right\} \sigma_{23} + i \frac{\Omega_{23}}{2} (\rho_{33} - \rho_{22}) - i \frac{\Omega_{13}}{2} \sigma_{21}$$



$\Delta = 0 \Rightarrow$ Ressonância de 1 fóton $|1\rangle \rightarrow |3\rangle$

$\delta, \delta_c = 0 \Rightarrow$ Ressonância de 2 fótons $|1\rangle \rightarrow |2\rangle$

Ressonância 1 fóton:

$$\omega_{31} - \omega_L = \Delta$$

Ressonância 2 fótons:

$$\omega_{21} - 2\omega_L = \delta_c$$

$$\Delta - \frac{\omega_{21}}{2} = \delta$$

1 único pulso

Caso particular: $\delta = \Delta = 0$

Condições iniciais:

$$\begin{cases} \rho_{11}(0) = 1 \\ \rho_{22}(0) = \rho_{33}(0) = \sigma_{ij}(0) = 0 \end{cases}$$

$$\rho_{33}(T_p) = \frac{1}{2} \frac{\mu_{13}^2}{\mu_{13}^2 + \mu_{23}^2} \left[1 - \cos \left(\frac{2E_0 T_p}{\hbar} \sqrt{\mu_{13}^2 + \mu_{23}^2} \right) \right]$$

Durante todo o seminário, consideraremos $\mu_{13} = \mu_{23}$. Desse modo,

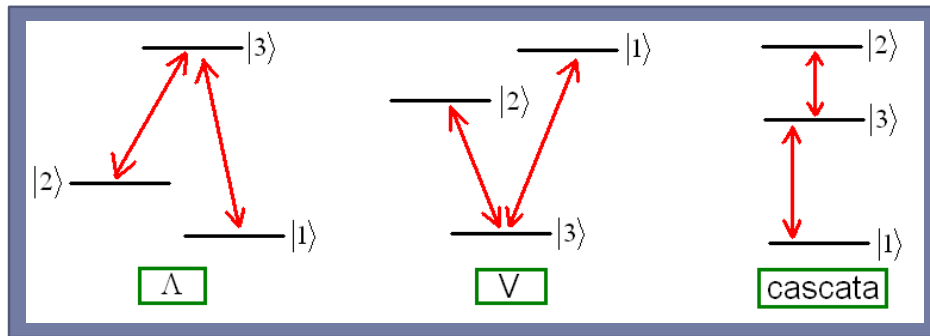
$$\rho_{33}(\theta) = \frac{1}{4} \left[1 - \cos(\theta\sqrt{2}) \right]$$

Da definição da frequência de Rabi para um sistema de 2 níveis, podemos tirar uma frequência de Rabi análoga para o nosso caso:

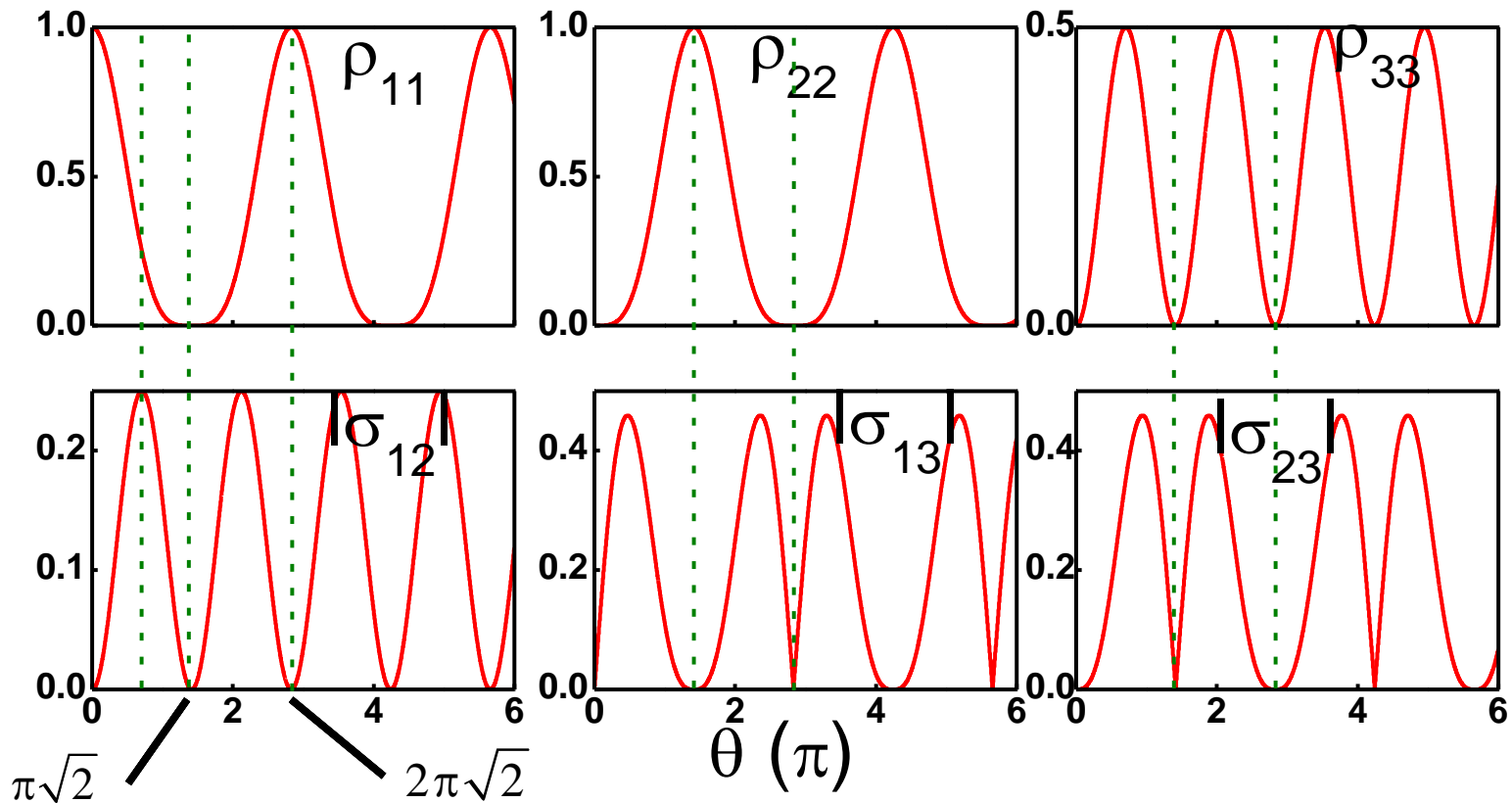
$$\Omega(t) = \frac{2\mu_{12}E_0}{\hbar} \rightarrow \Omega_{3N}(t) = \frac{2E_0(t)\sqrt{\mu_{13}^2 + \mu_{23}^2}}{\hbar}$$

$$\theta_{3N} = \int_{-\infty}^{\infty} \Omega_{3N}(t) dt$$

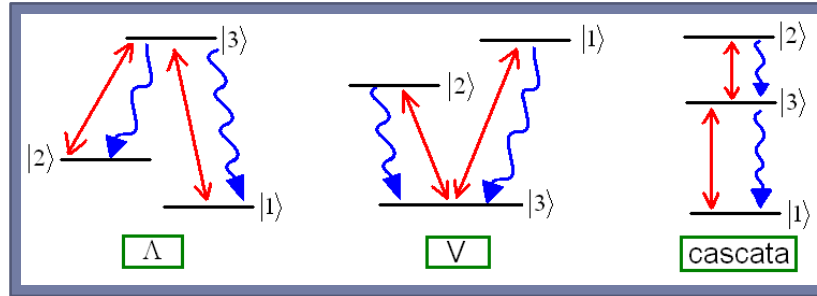
1 único pulso



$$\rho_{33}(\theta) = \frac{1}{4} \left[1 - \cos(\theta\sqrt{2}) \right]$$



Interação com o trem de pulsos



$$\frac{\partial \rho_{11}}{\partial t} = \left\{ -i \frac{\Omega_{13}}{2} \sigma_{13} + \text{c.c.} \right\} + \rho_{11}^{\text{Rel}}$$

$$\frac{\partial \rho_{22}}{\partial t} = \left\{ -i \frac{\Omega_{23}}{2} \sigma_{23} + \text{c.c.} \right\} + \rho_{22}^{\text{Rel}}$$

$$\frac{\partial \rho_{33}}{\partial t} = \left\{ i \frac{\Omega_{13}}{2} \sigma_{13} + \text{c.c.} \right\} + \left\{ i \frac{\Omega_{23}}{2} \sigma_{23} + \text{c.c.} \right\} + \rho_{33}^{\text{Rel}}$$

$$\frac{\partial \sigma_{12}}{\partial t} = i \left\{ \begin{array}{c} 2(\Delta - \delta) \\ \delta_c \end{array} \right\} \sigma_{12} + i \frac{\Omega_{13}}{2} \sigma_{32} - i \frac{\Omega_{23}}{2} \sigma_{13} - \frac{\sigma_{12}}{T_{12}}$$

$$\frac{\partial \sigma_{13}}{\partial t} = i \left\{ \begin{array}{c} \Delta \\ \Delta \end{array} \right\} \sigma_{13} + i \frac{\Omega_{13}}{2} (\rho_{33} - \rho_{11}) - i \frac{\Omega_{23}}{2} \sigma_{12} - \frac{\sigma_{13}}{T_{13}}$$

$$\frac{\partial \sigma_{23}}{\partial t} = i \left\{ \begin{array}{c} 2\delta - \Delta \\ \delta_c - \Delta \end{array} \right\} \sigma_{23} + i \frac{\Omega_{23}}{2} (\rho_{33} - \rho_{22}) - i \frac{\Omega_{13}}{2} \sigma_{21} - \frac{\sigma_{23}}{T_{23}}$$

Inclusão dos termos de relaxação:

$$\rho_{11}^{\text{Rel}} = + \frac{\rho_{33}}{2T_{33}}$$

$$\rho_{22}^{\text{Rel}} = + \frac{\rho_{33}}{2T_{33}}$$

$$\rho_{33}^{\text{Rel}} = - \frac{\rho_{33}}{T_{33}}$$

$$T_{11} = T_{22} = \infty$$

Λ

$$\frac{1}{T_{ij}} = \frac{1}{2} \left(\frac{1}{T_{ii}} + \frac{1}{T_{jj}} \right)$$

Evolução temporal: Sistema lambda

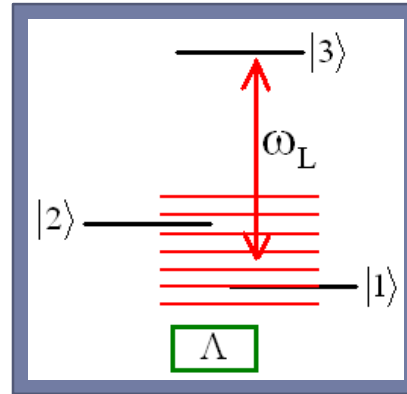
Parâmetros:

$$\theta = \pi/10$$

$$T_R = 10 \text{ ns}$$

$$T_{33} = 25 \text{ ns}$$

$$\omega_{21} = \omega_2 - \omega_1 \ll \Delta\omega_L$$



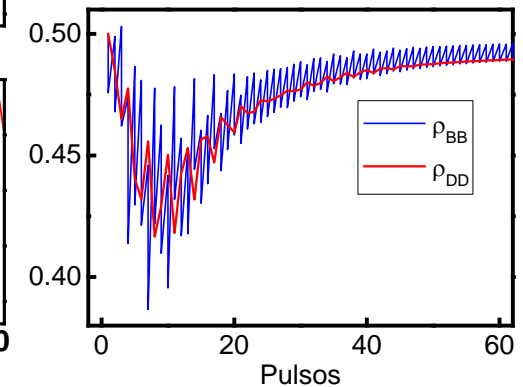
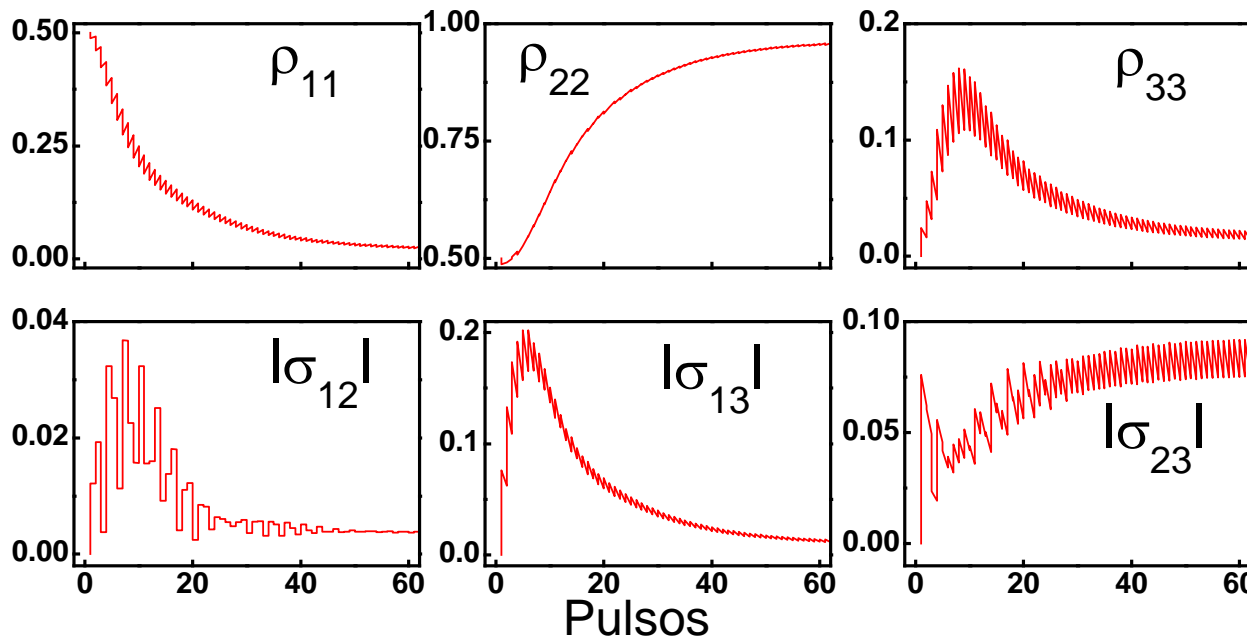
$$\omega_{21} \neq n f_R$$

$$\omega_{n_i} = \omega_{31}$$

$$\omega_{n_j} \neq \omega_{32}$$

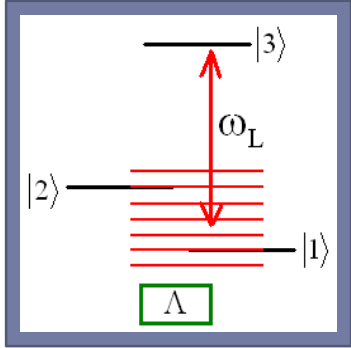
$$|B\rangle = \frac{1}{\sqrt{2}}(|1\rangle + |2\rangle)$$

$$|D\rangle = \frac{1}{\sqrt{2}}(|1\rangle - |2\rangle)$$



Bombeamento óptico

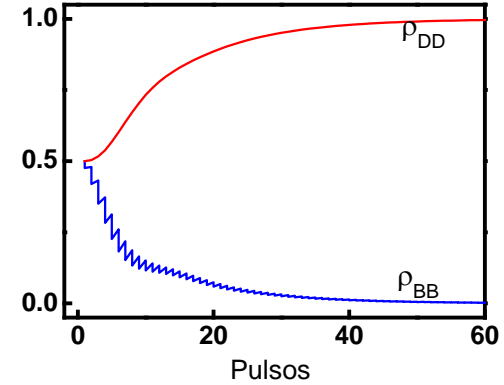
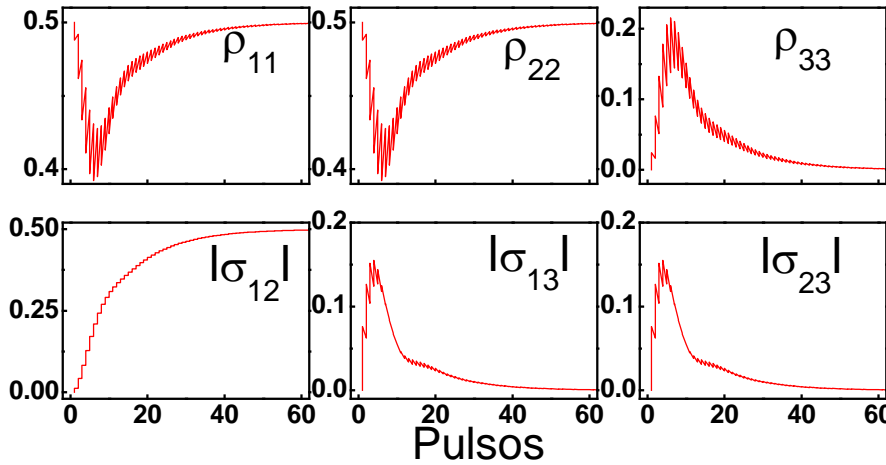
Evolução temporal: Sistema lambda



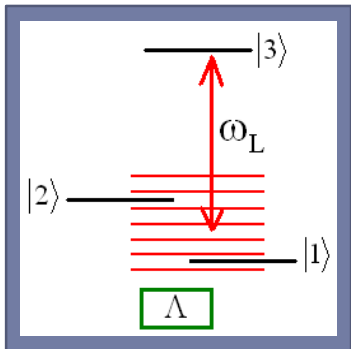
$$\omega_{21} = n f_R$$

$$\omega_{n_i} = \omega_{31}$$

$$\omega_{n_j} = \omega_{32}$$



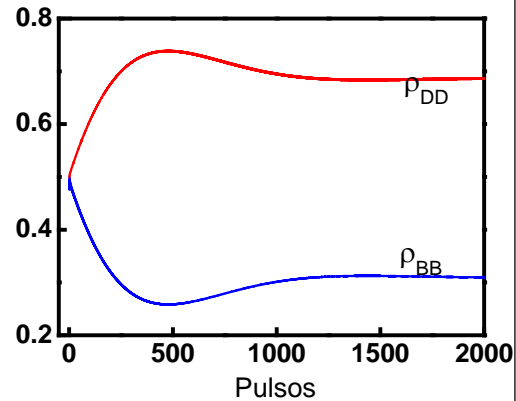
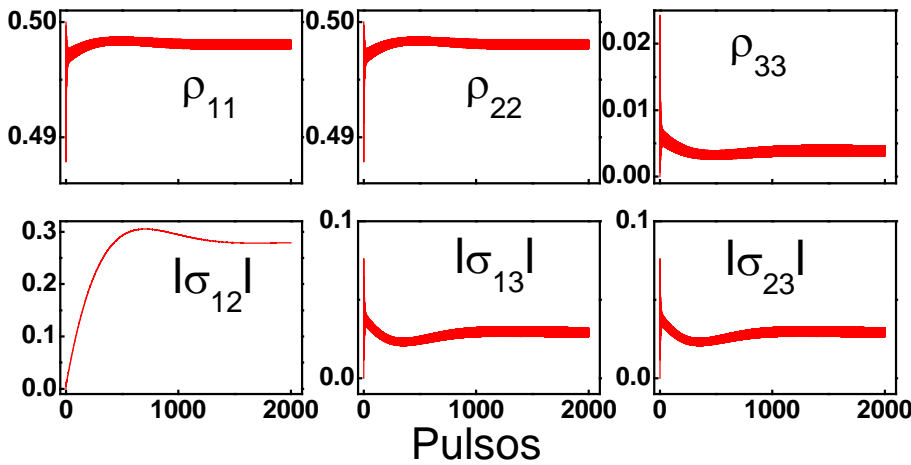
Caso degenerado → Soares and de Araujo, PRA (2007)



$$\omega_{21} = n f_R$$

$$\omega_{n_i} \neq \omega_{31}$$

$$\omega_{n_j} \neq \omega_{32}$$

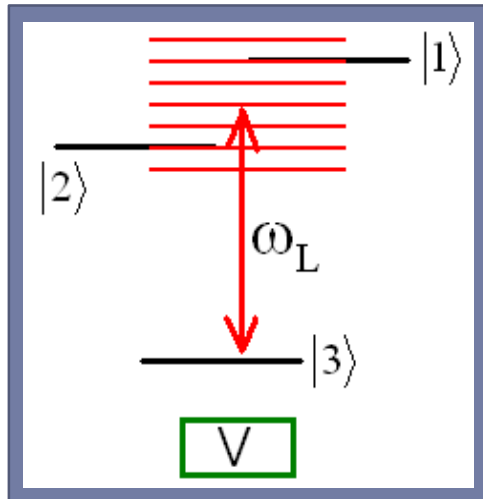
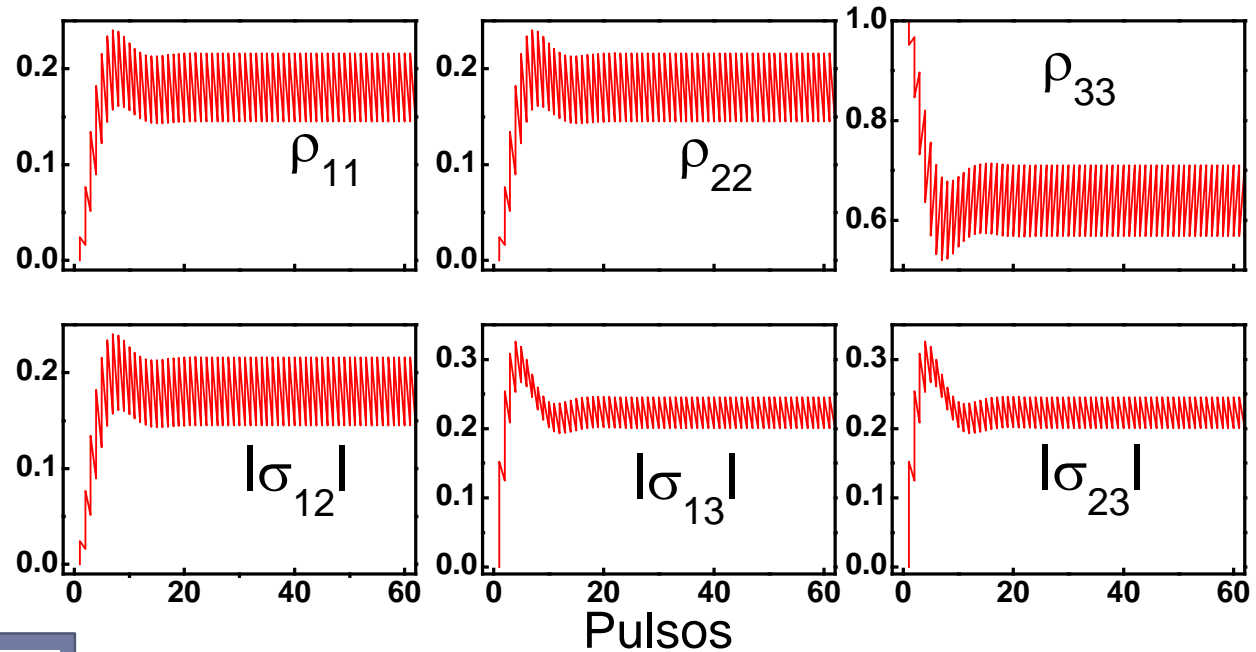


Evolução temporal: Sistema Vee

Parâmetros:

$$T_{11} = T_{22} = 25 \text{ ns}$$

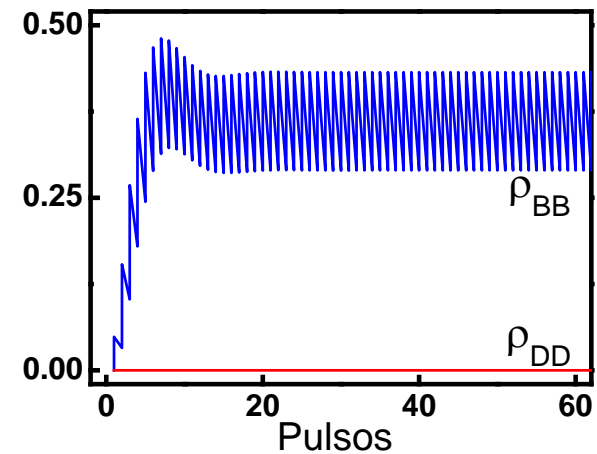
$$\theta = \pi/10$$



$$\omega_{12} = n f_R$$

$$\omega_{n_i} = \omega_{13}$$

$$\omega_{n_j} = \omega_{23}$$



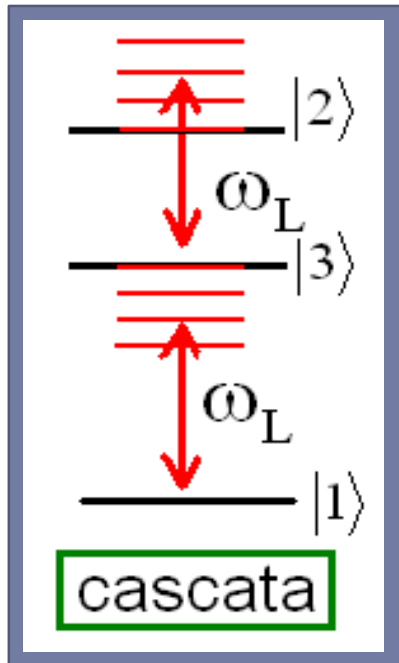
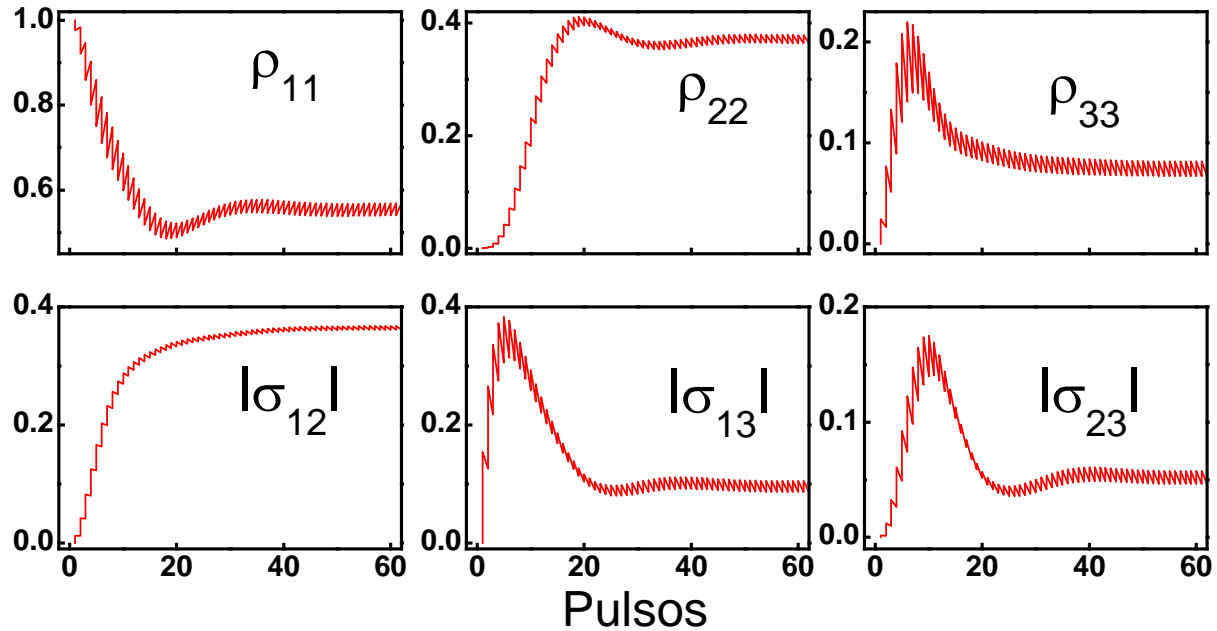
Evolução temporal: Sistema cascata

Parâmetros:

$$T_{22} = 250 \text{ ns}$$

$$T_{33} = 25 \text{ ns}$$

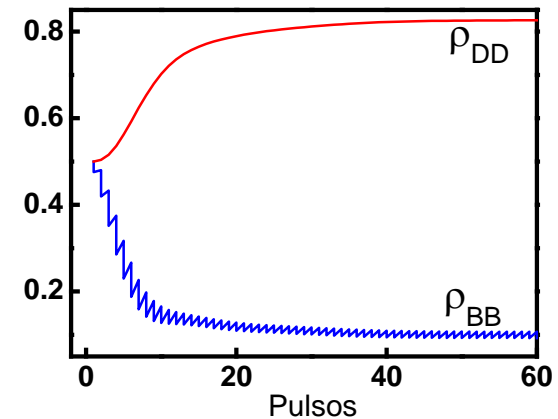
$$\theta = \pi/10$$



$$\omega_{21} = n f_R$$

$$\omega_{n_i} = \omega_{31}$$

$$\omega_{n_j} = \omega_{23}$$



Estudo em função da área do pulso

Parâmetros:

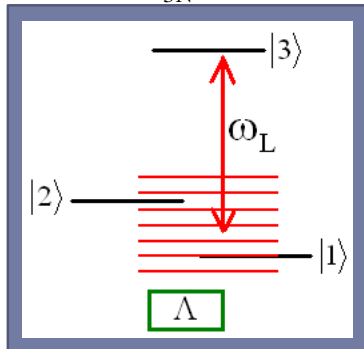
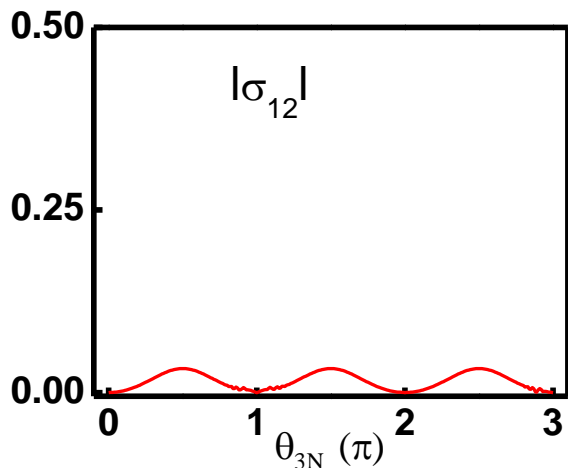
Sistema Λ

$T_{33} = 25$ ns

Ressonância de 1 fóton

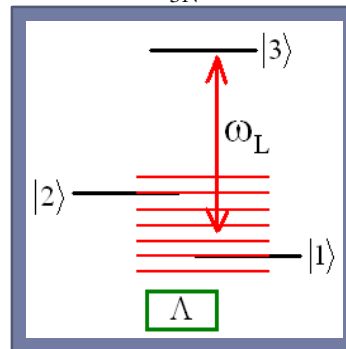
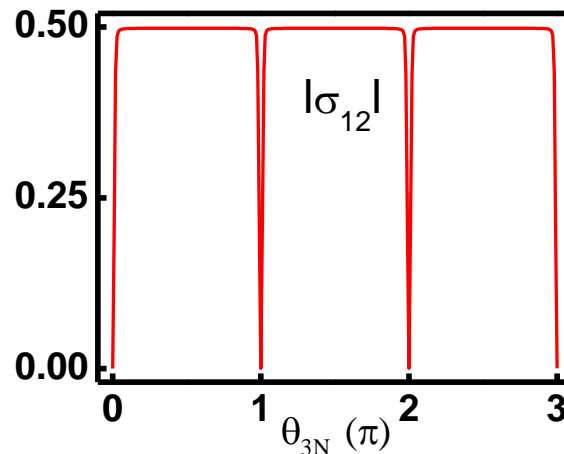
$|1\rangle \rightarrow |3\rangle$

$N = 120$ pulsos



Ressonância de 1 e de 2 fótons

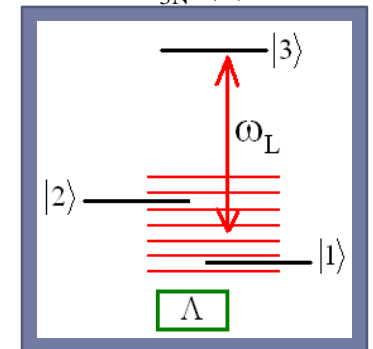
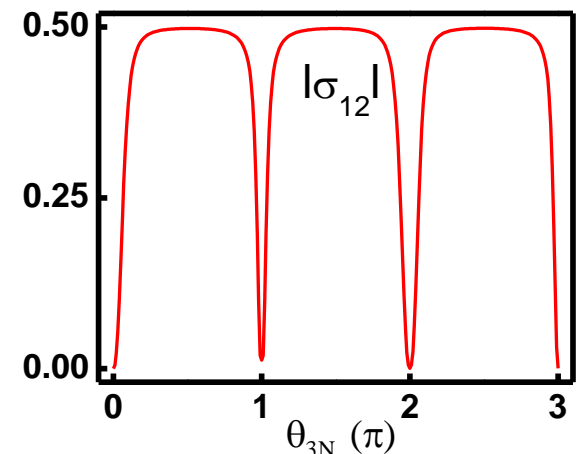
$N = 120$ pulsos



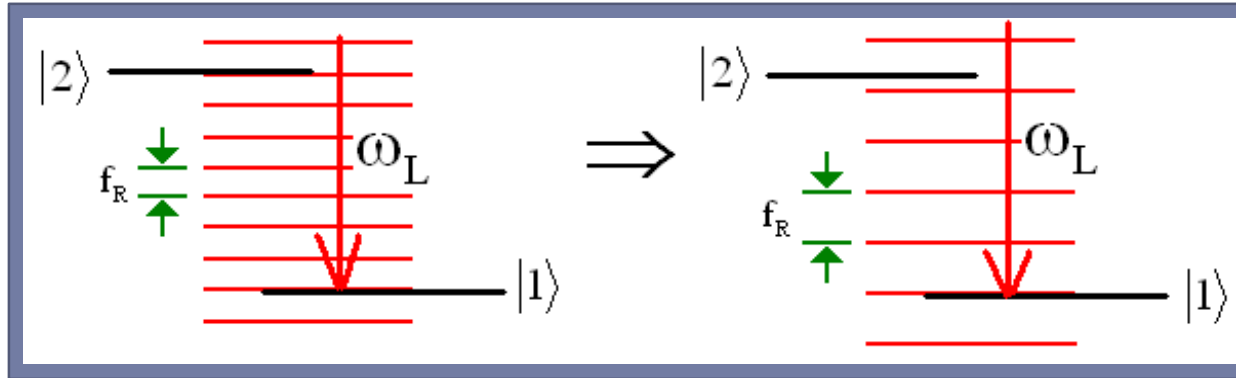
Ressonância de 2 fótons

$|1\rangle \rightarrow |2\rangle$

$N = 2000$ pulsos



Estudo em função da taxa de repetição do laser - f_R

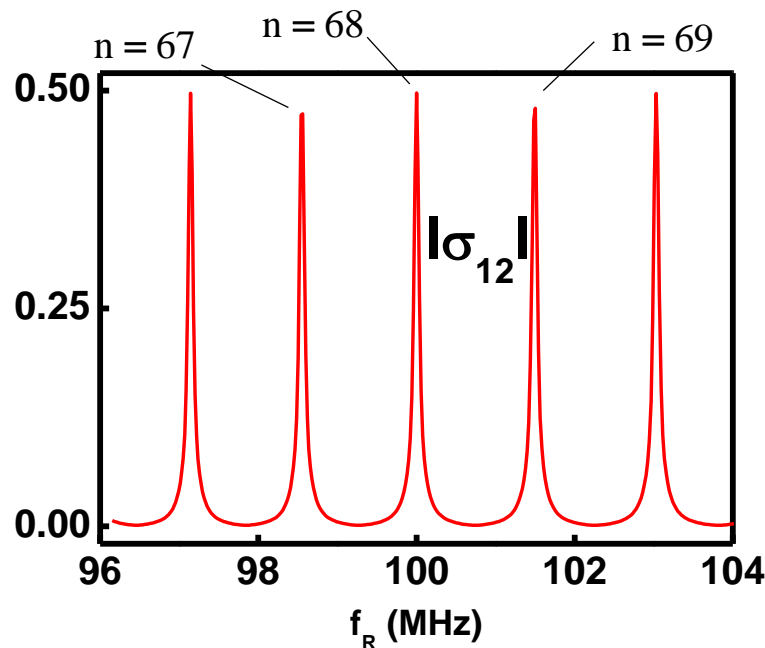


Parâmetros:

$$T_{33} = 25 \text{ ns}$$

$$\theta = \pi/10$$

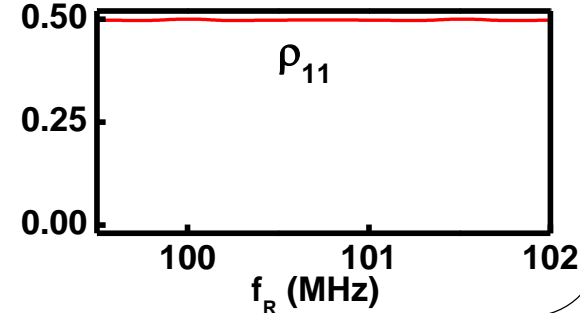
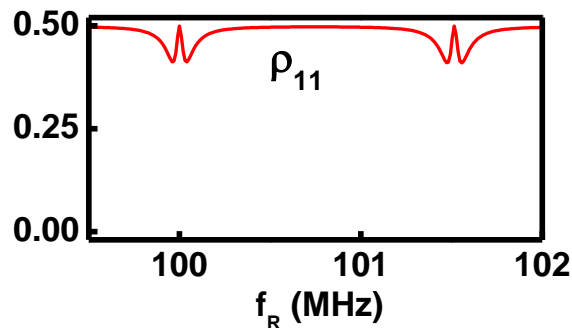
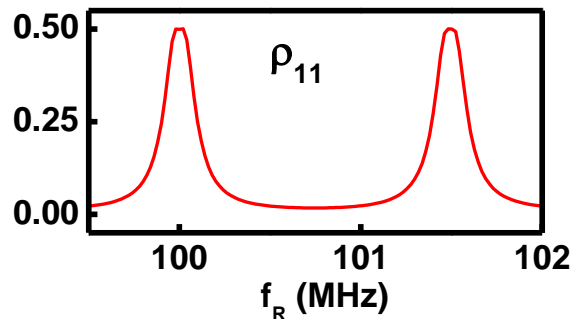
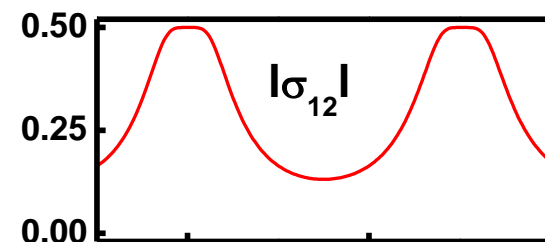
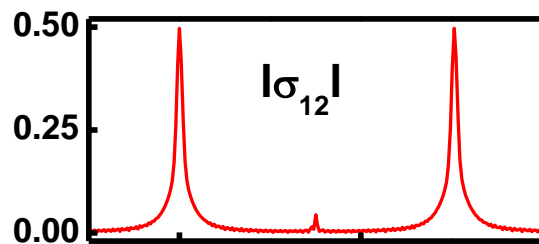
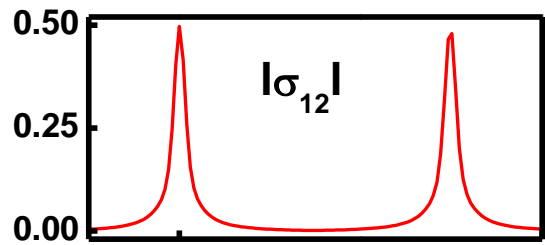
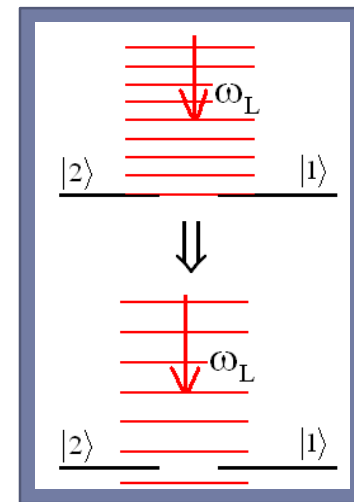
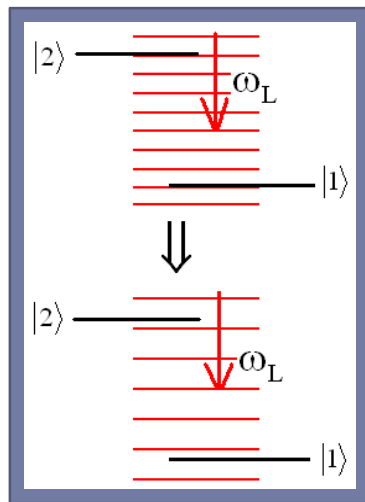
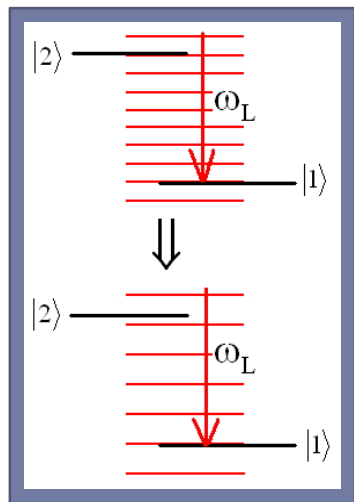
$$N = 120 \text{ pulsos}$$



$$\omega_{21} = 6800 \text{ MHz fixo}$$

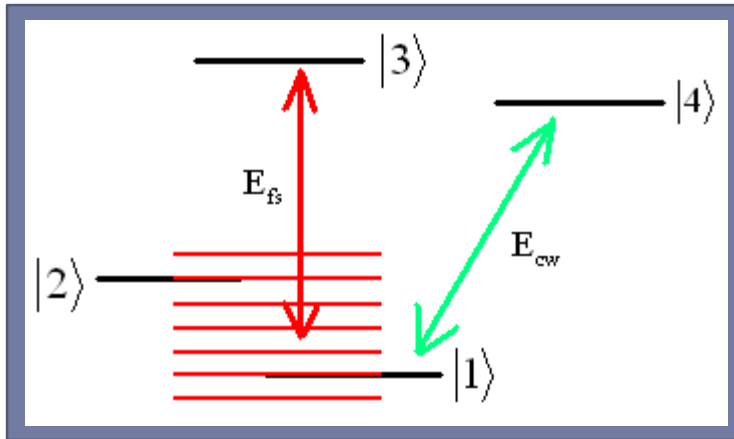
$$f_R = \frac{\omega_{21}}{n}, \text{ n inteiro}$$

Estudo em função da taxa de repetição do laser - f_R



Perspectivas: indo para o laboratório

Usar um laser de diodo cw para sondar o estado $|1\rangle$ enquanto a taxa de repetição do laser de femtosegundos é variada.



$N = 120$ pulsos

$$\theta_{3N}^{\text{fs}} = \pi/10$$

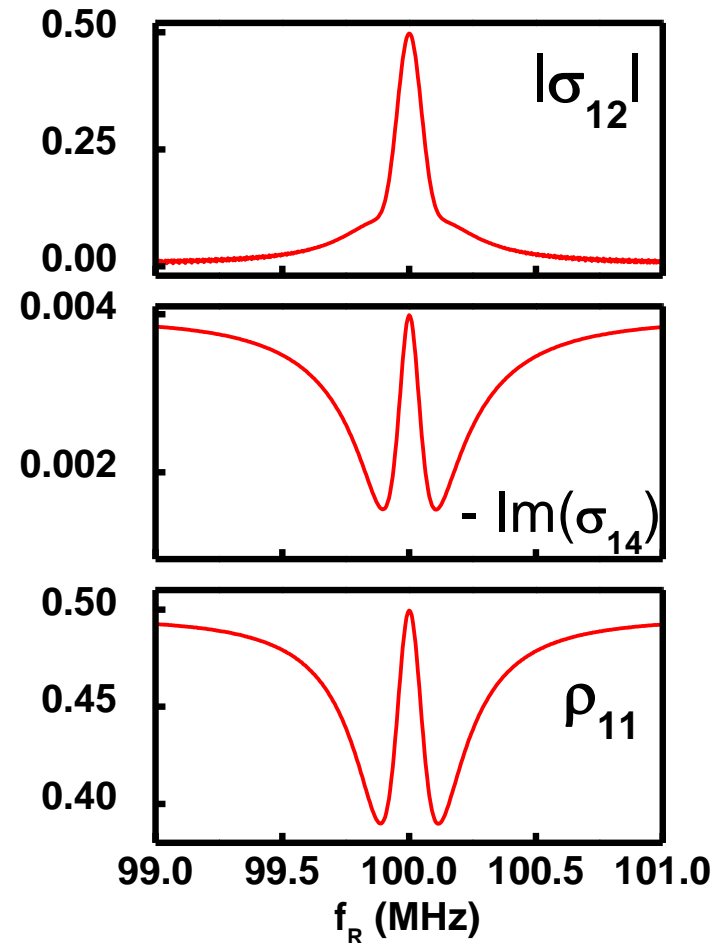
$$\theta^{\text{cw}} = \pi/1000$$

E_{cw} na ressonância $|1\rangle \rightarrow |4\rangle$

$$T_R = 10 \text{ ns} \Rightarrow f_R = 100 \text{ MHz}$$

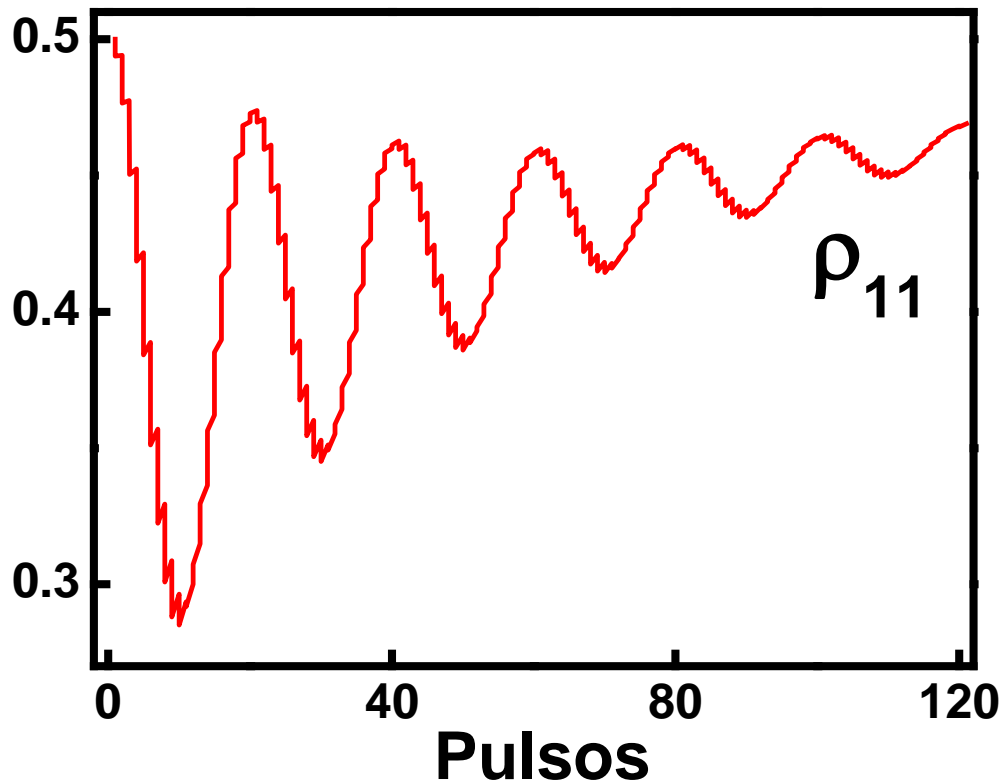
$$T_{33} = T_{44} = 25 \text{ ns}$$

$$\omega_{21} = 6800 \text{ MHz}$$



Perspectivas

Usar um laser de femtosegundos com taxa de repetição de **1 GHz**, o que implica numa separação entre os pulsos de **1 ns**.



Regime quase-cw

sistema Λ

$$\theta_{3N} = \pi/10$$

$$f_R = 1 \text{ GHz}$$

$$T_{33} = 25 \text{ ns}$$

$$\omega_{21} = 6 \text{ GHz}$$

$$T_R = 1 \text{ ns}$$

$$\theta_{3N} = \Omega T_R \Rightarrow \Omega = \frac{\theta_{3N}}{T_R}$$

$$\Omega / 2\pi = 50 \text{ MHz}$$

Oscilações de Rabi

Conclusões

Estudamos um sistema de 3 níveis interagindo com um trem de pulsos, onde variamos a taxa de repetição do laser, o número de pulsos e a área do pulso.

Nos sistemas Λ e cascata consegue-se colocar uma boa parte de átomos no estado escuro.

O tempo de vida relativamente da coerência entre os estados 1 e 2 do sistema V não torna possível a criação de um estado escuro nesse tipo de sistema.

Observamos efeitos como bombeamento ótico, armazenamento coerente de população e transições Raman.