Parametric four-wave mixing in atomic vapor induced by a frequency-comb and a cw laser

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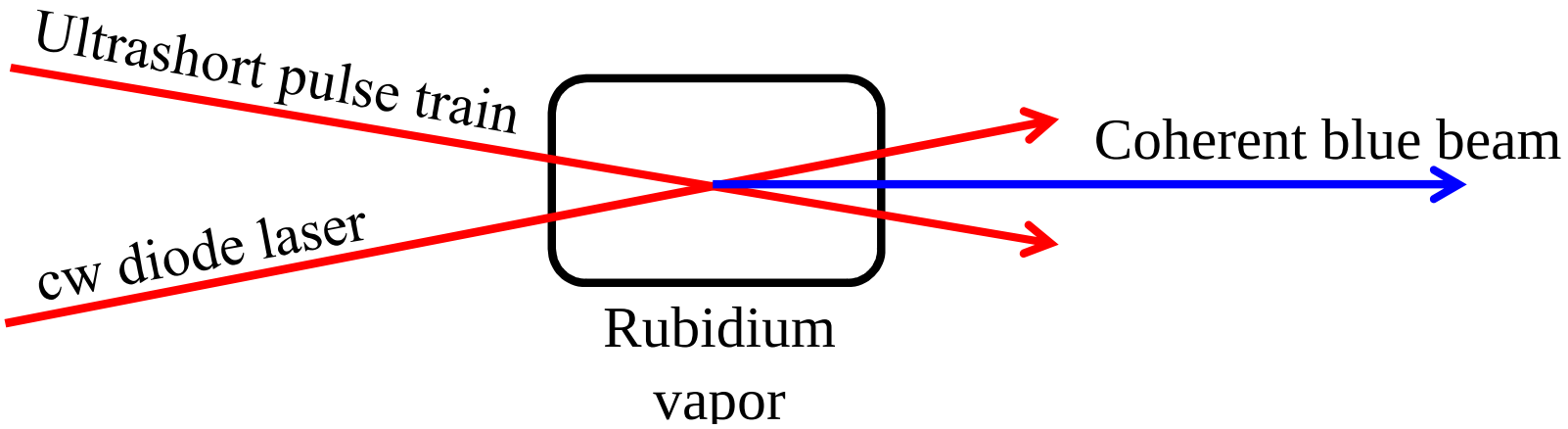
Universidade Federal de Pernambuco

Marco P. M. de Souza
Universidade Federal de Rondônia

Goal

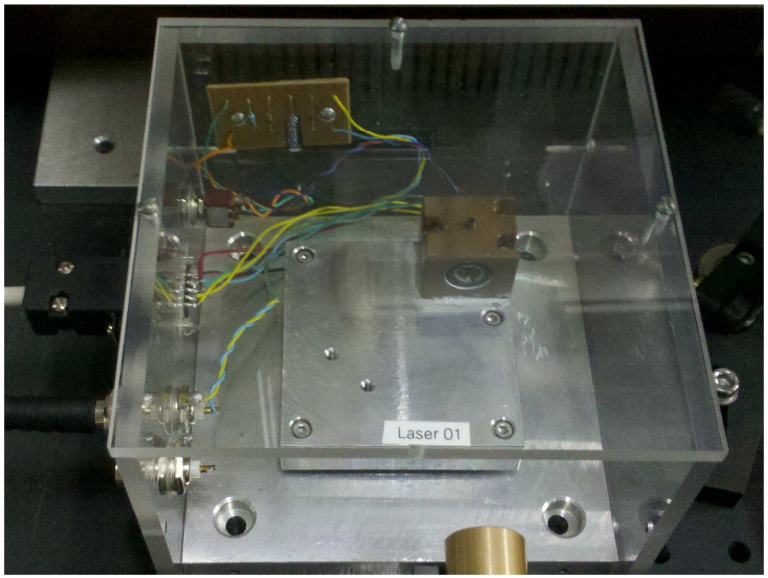
- The objective is to study the coherent blue light generated in rubidium vapor by four wave mixing due to the combined action of an ultrashort pulse train and a cw diode laser.



Outline

1. Lasers
2. Atomic system
3. Four-wave mixing
4. Correlated work
5. Setup
6. Experimental Results
7. Theory
8. Conclusions

Diode laser



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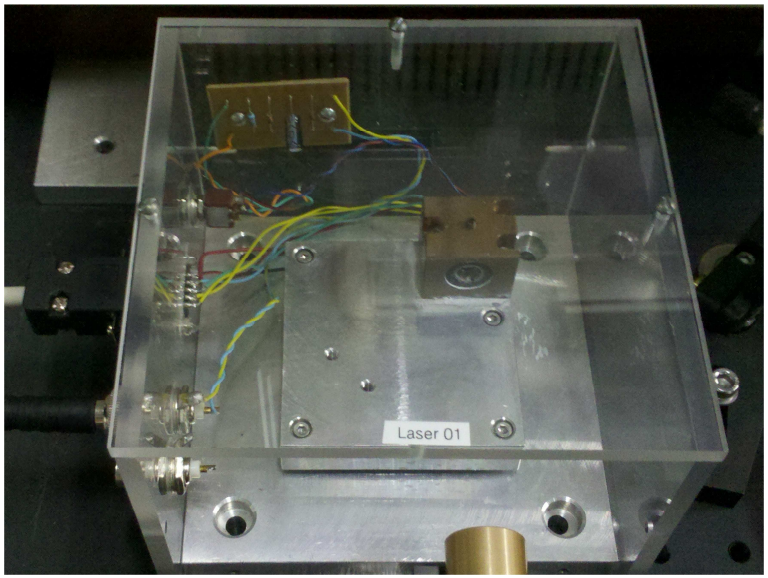

- Power = 30 mW
- Linewidth < 1 MHz
- $\lambda = 780$ nm
- Scan frequency = 10 GHz

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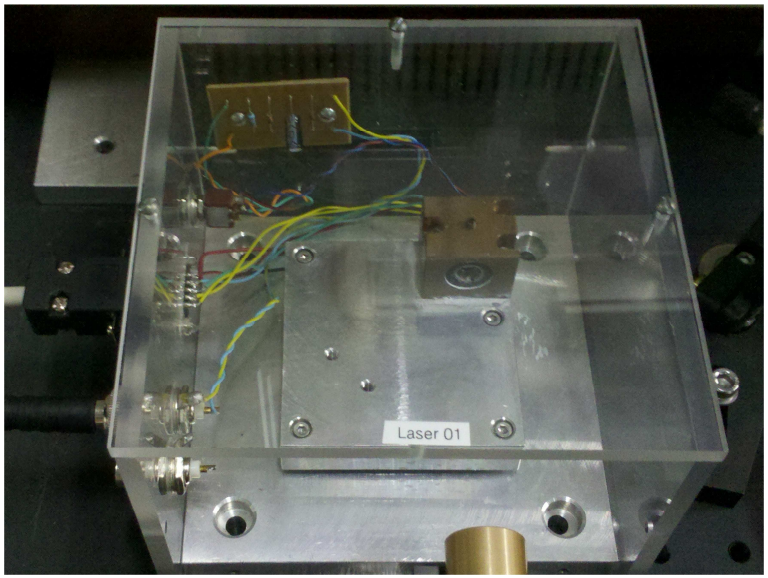

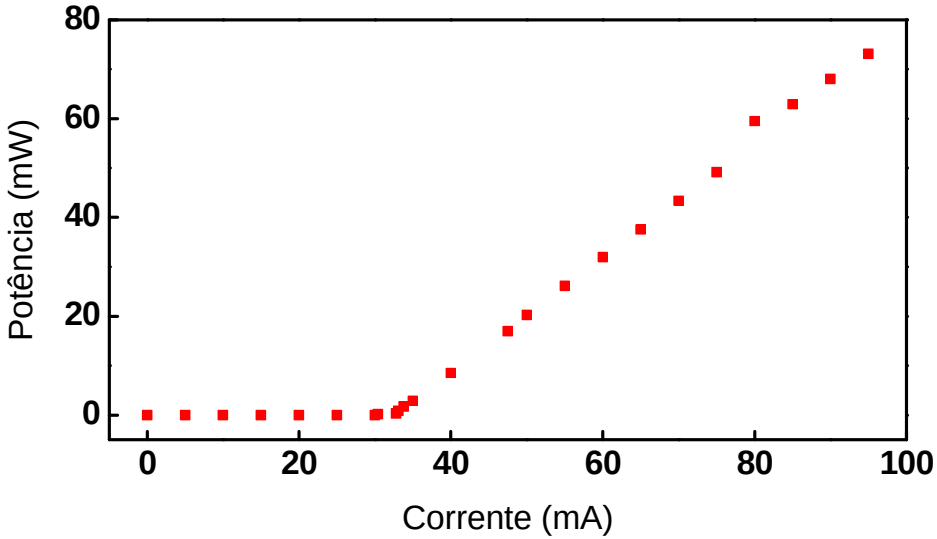

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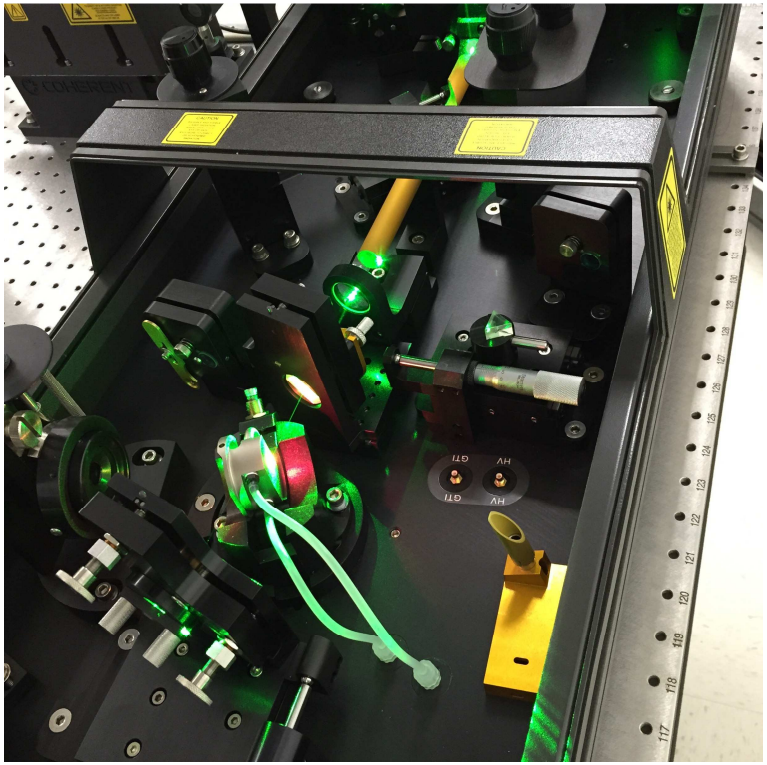
$$E(t) = E_0 e^{i\omega_{cw} t}$$

Femtosecond laser



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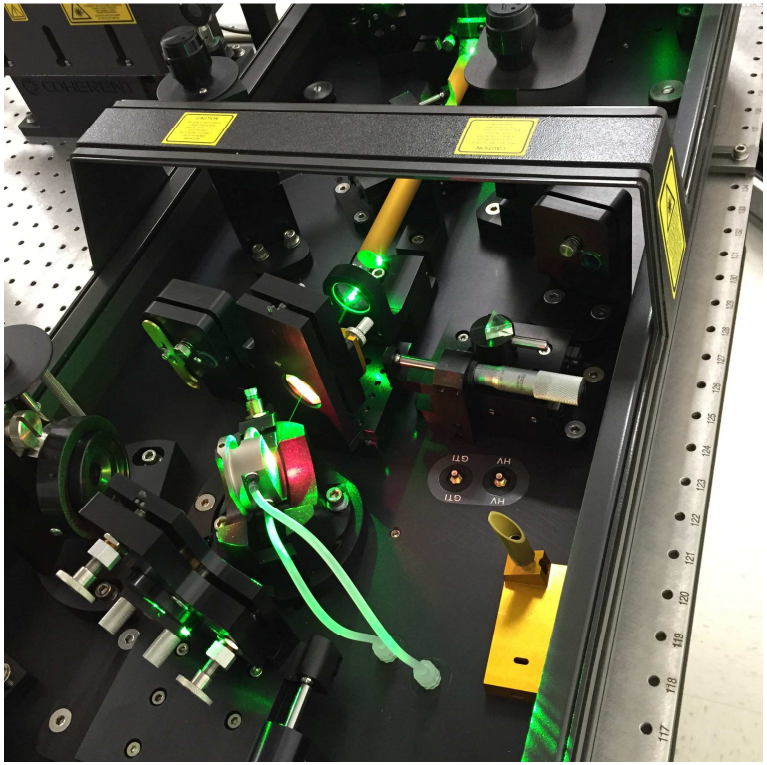

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- Peak power = 50 kW
- Repetition rate = 76 MHz
- Temporal width = 150 fs

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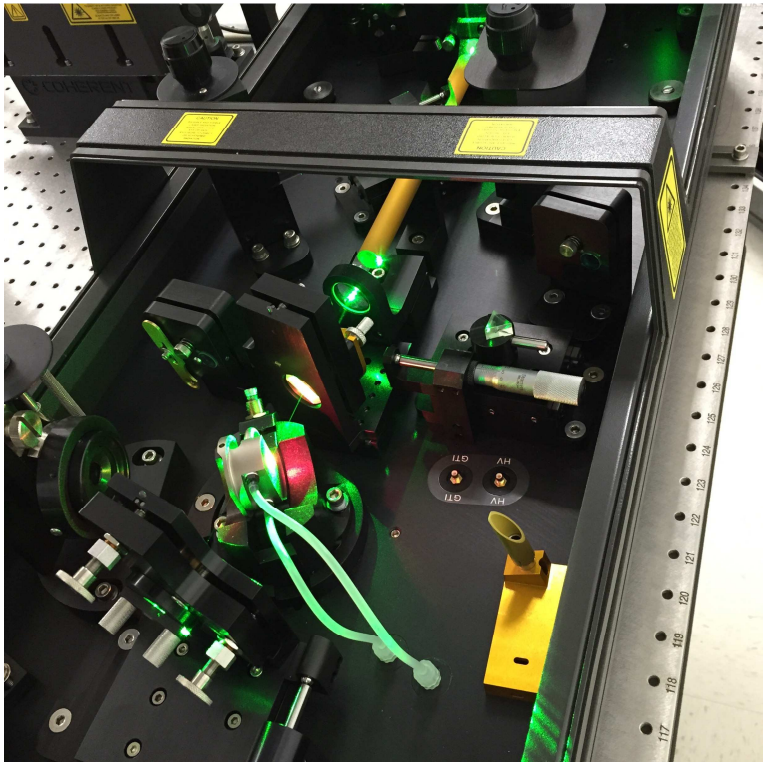

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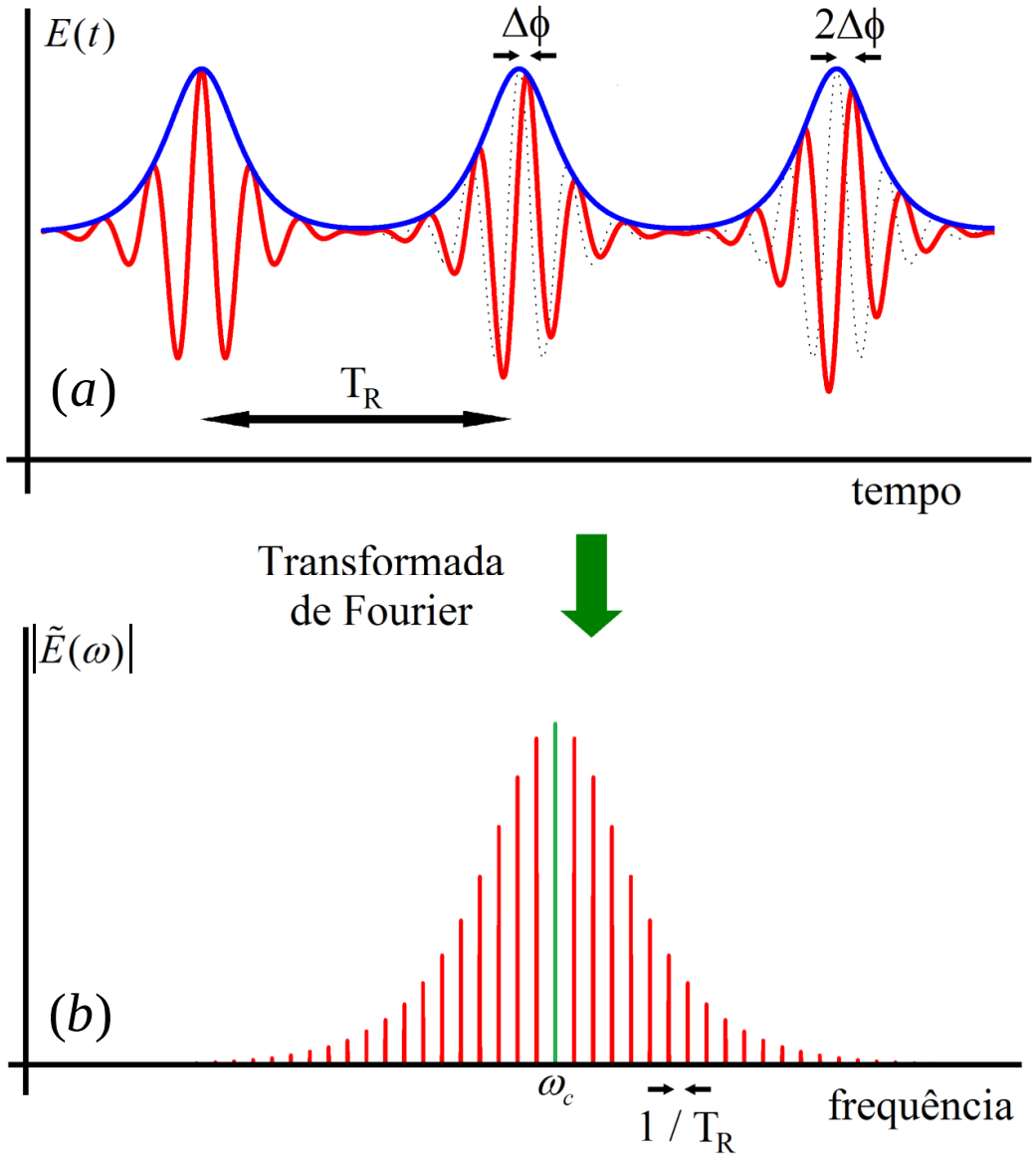
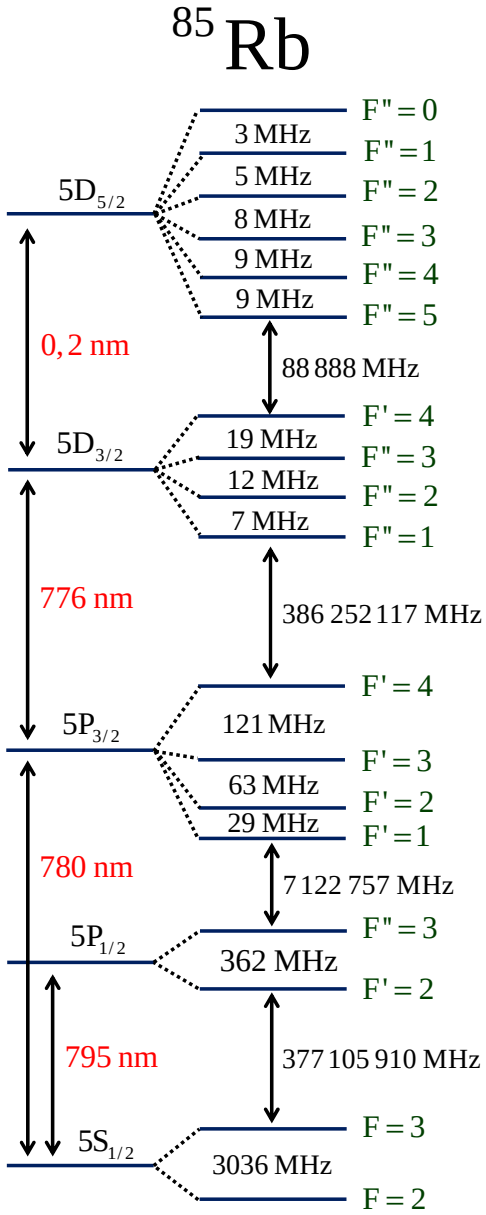
$$E(t) = E_0 \sum_{n=0}^{N-1} \text{sech}\left[\frac{1.76(t - nT_R)}{T_p}\right] e^{in(\omega_{fs}T_R - \phi) + i\omega_{fs}t}$$

Femtosecond laser



Atomic system



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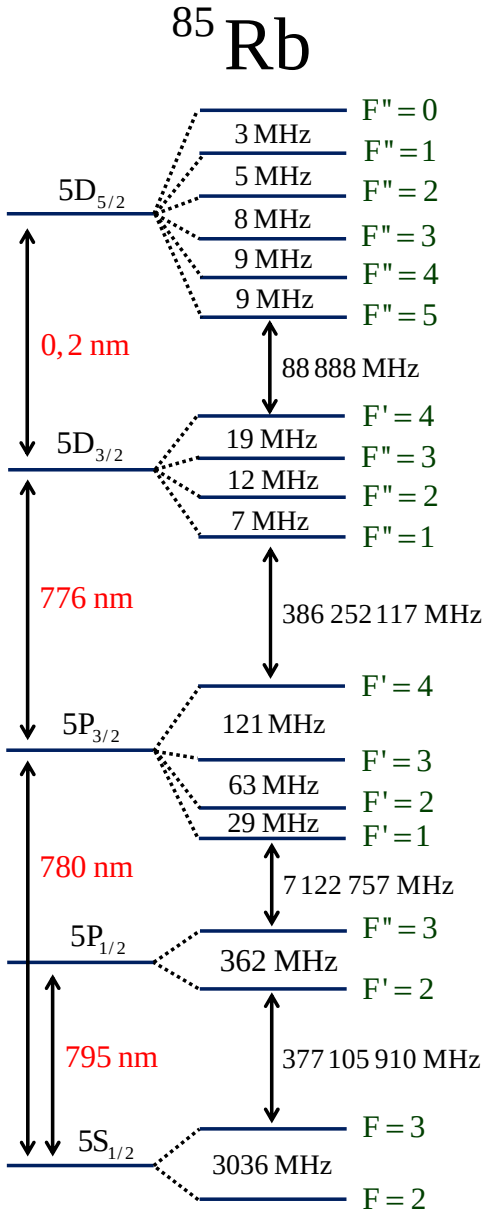

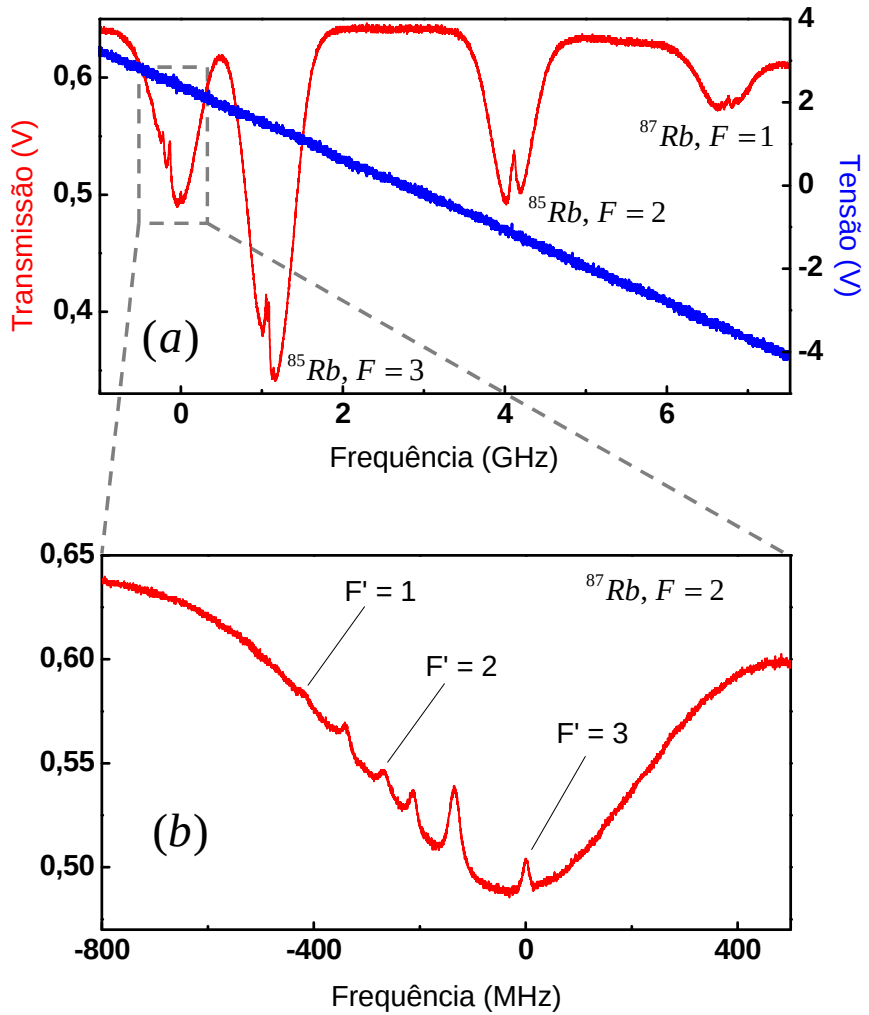

Four-wave mixing

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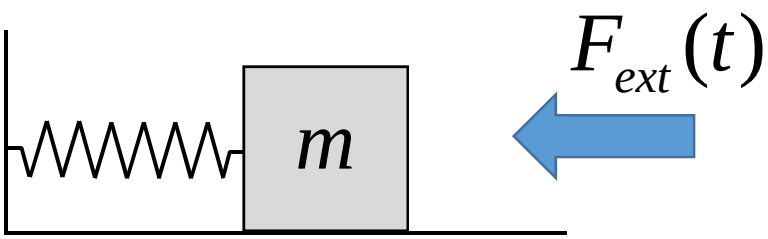
- In the weak interaction limit, it is a third-order process, where the generated field can be expressed as

$$P_4 = \epsilon_0 \chi^{(3)} E_1 E_2 E_3$$

Driven nonlinear oscillator: classical analysis



- Nonlinear spring:
  $F_{el} = -kx - k_2 x^2$
- $F_{ext}(t) = F_0 \left(\cos \omega_1 t + \cos \omega_2 t\right)$

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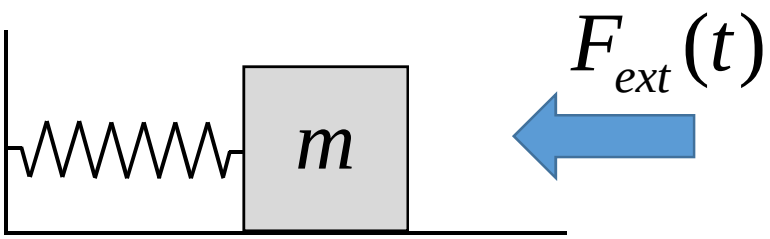

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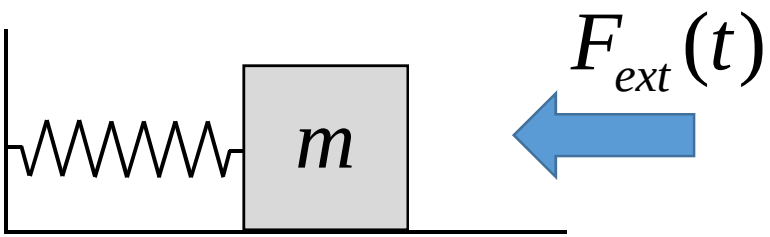

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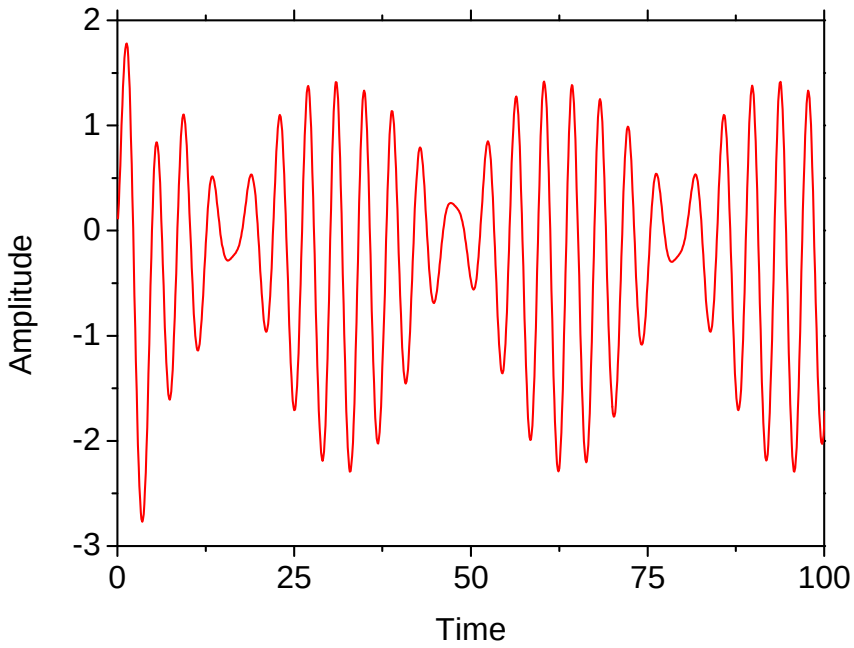

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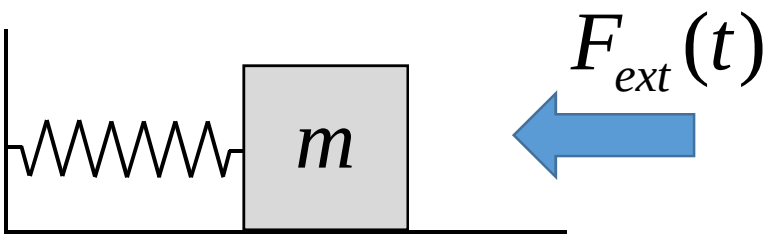

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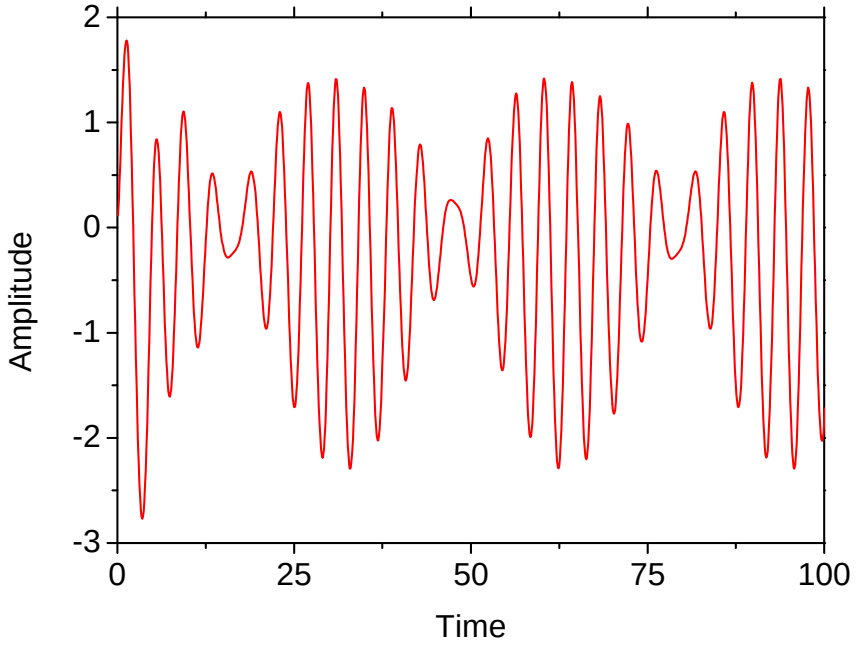

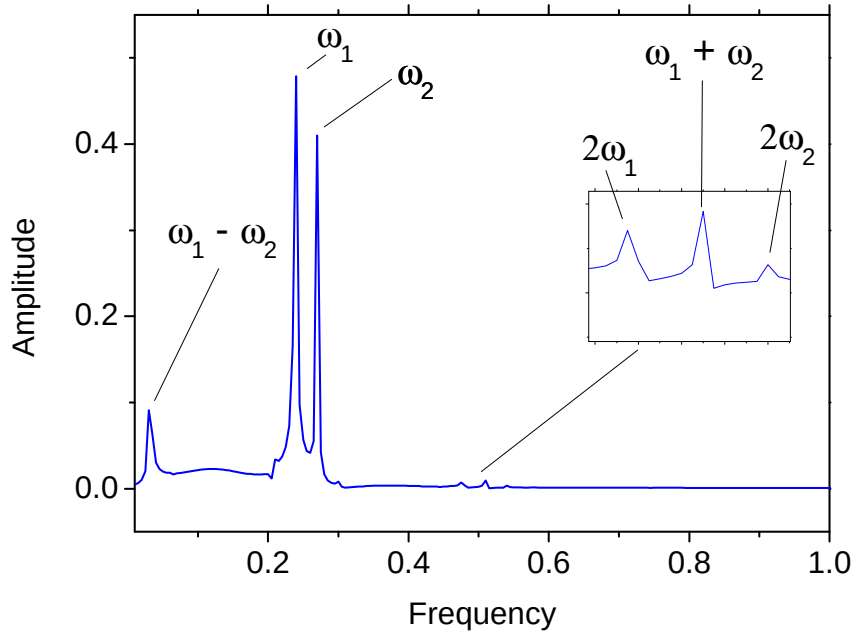

Wave-mixing

$$\omega_1, \omega_2 \longrightarrow \begin{cases} \omega_1 \\ \omega_2 \\ 2\omega_1 \\ 2\omega_2 \\ \omega_1 + \omega_2 \\ \omega_1 - \omega_2 \end{cases}$$

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General formula:

$$\omega_1, \omega_2, \omega_3, \ldots \longrightarrow \alpha_1\omega_1 \pm \alpha_2\omega_2 \pm \alpha_3\omega_3 \pm \cdots$$

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Electromagnetism:

$$P = \epsilon_0\chi^{(1)}E + \epsilon_0\chi^{(2)}E^2 + \epsilon_0\chi^{(3)}E^3 + \cdots$$

$$\begin{aligned} \chi^{(1)} &\approx 1 \\ \chi^{(2)} &\approx 10^{-12}\ m/V \\ \chi^{(3)} &\approx 10^{-24}\ m^2/V^2 \end{aligned}$$

Correlated work

#118375 - $15.00 USD Received 9 Oct 2009; revised 20 Nov 2009; accepted 20 Nov 2009; published 30 Nov 2009
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7 December 2009 / Vol. 17, No. 25 / OPTICS EXPRESS 22861

Coherent and collimated blue light generated by four-wave mixing in Rb vapour

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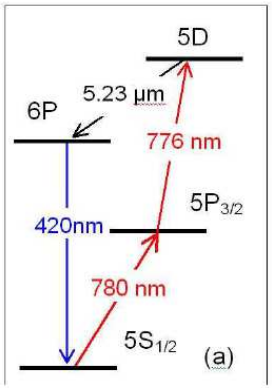

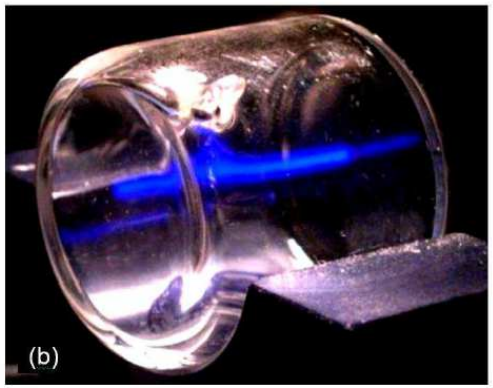

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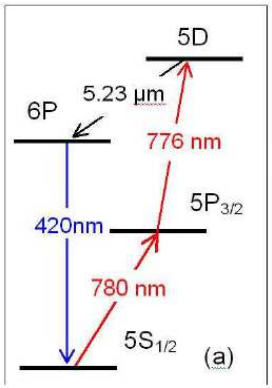
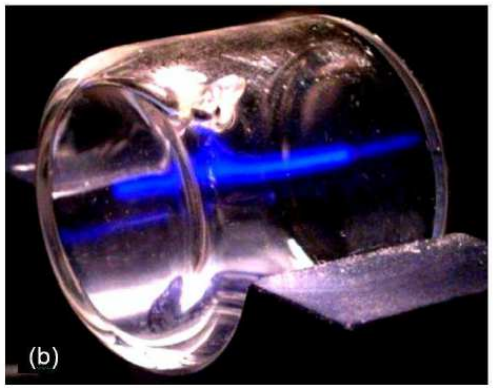
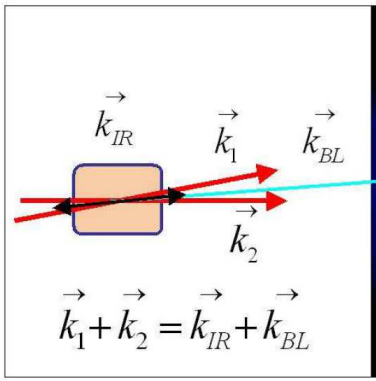
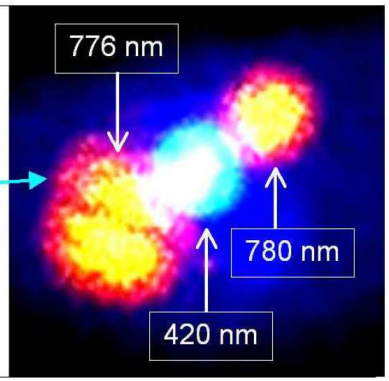
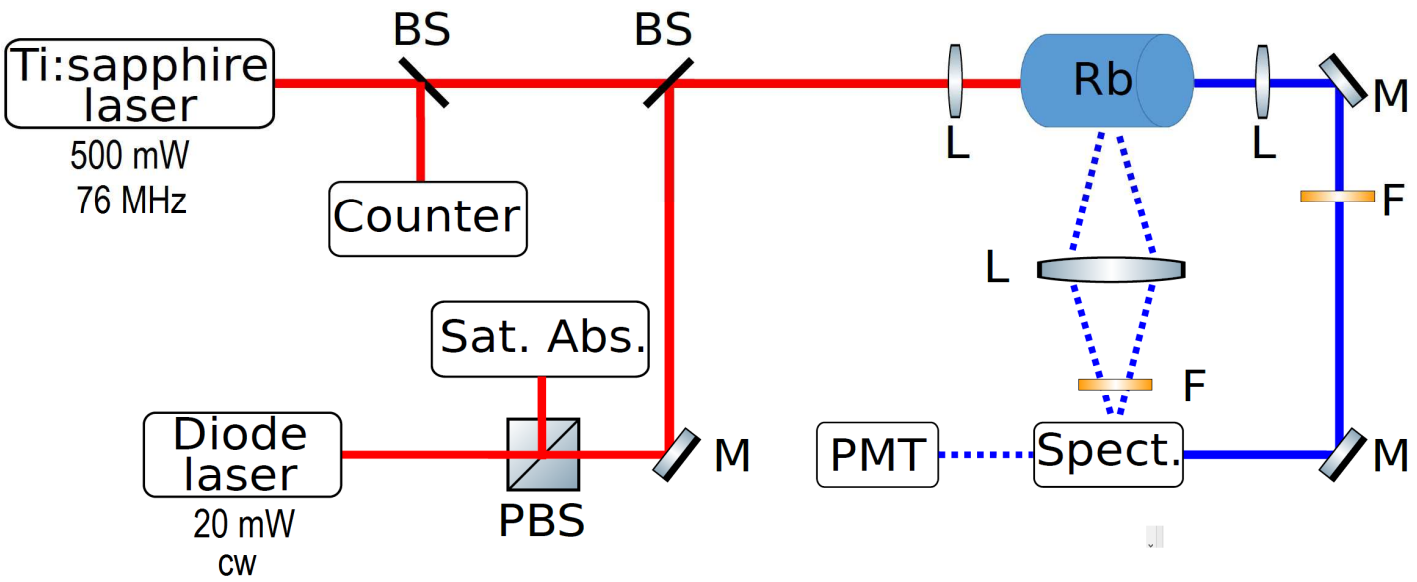


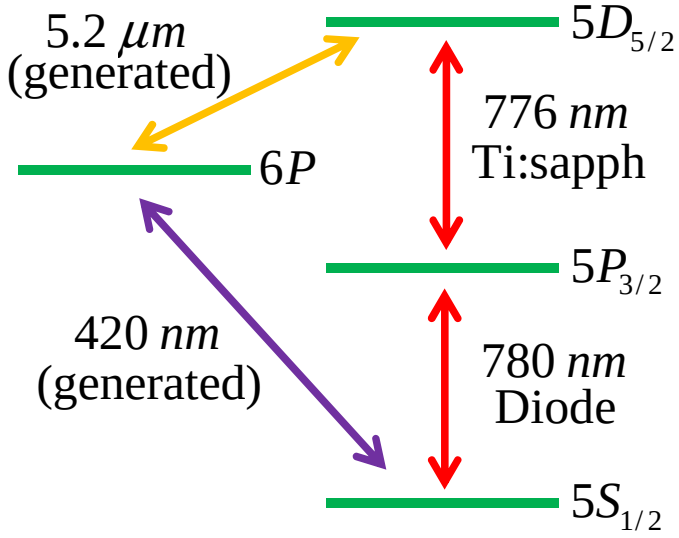




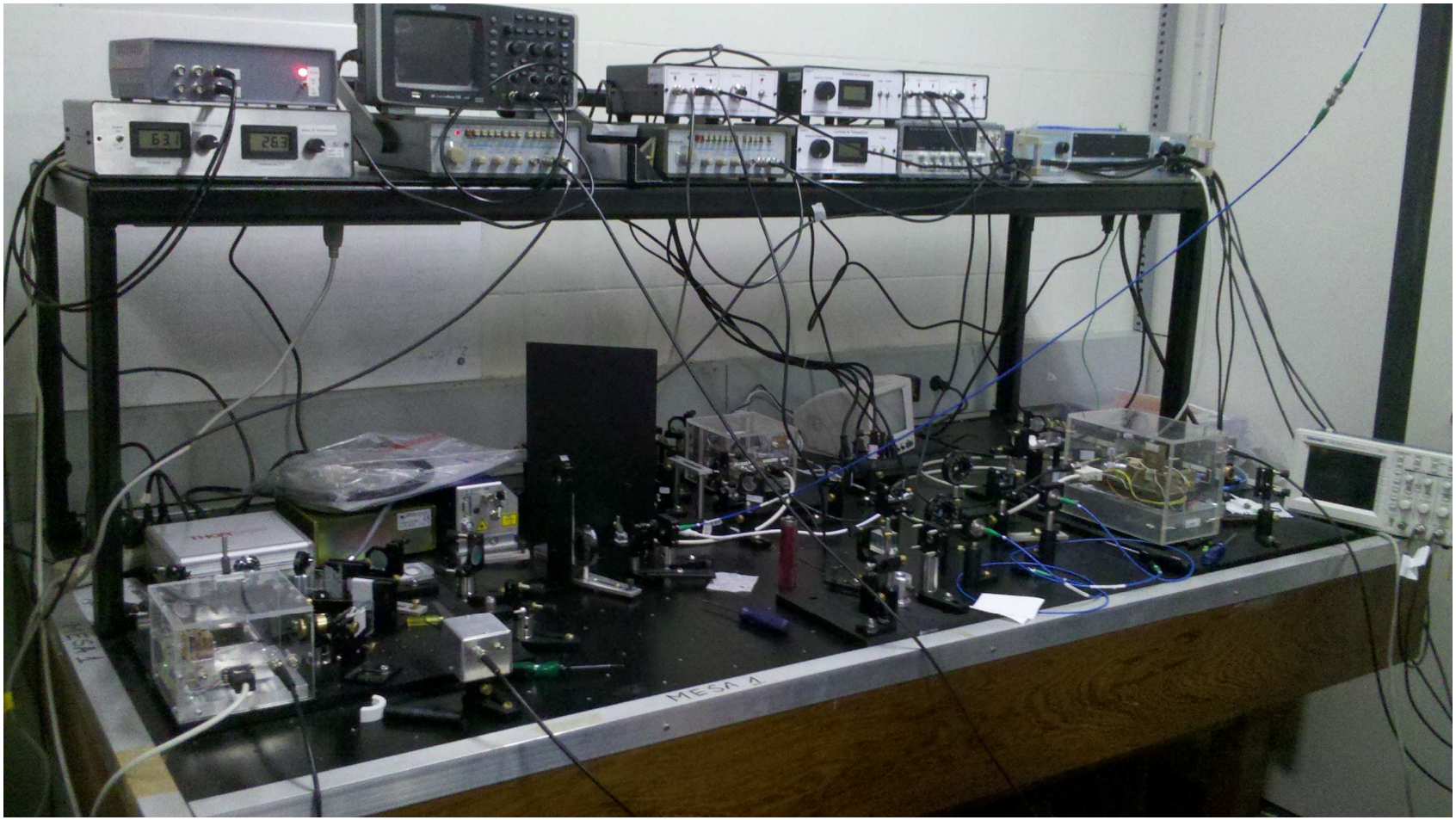


Setup


Ti:sapphire laser
500 mW
76 MHz
BS
BS
Counter
Sat. Abs.
Diode laser
20 mW
cw
PBS
M
L
Rb
L
M
F
L
F
PMT
Spect.
M

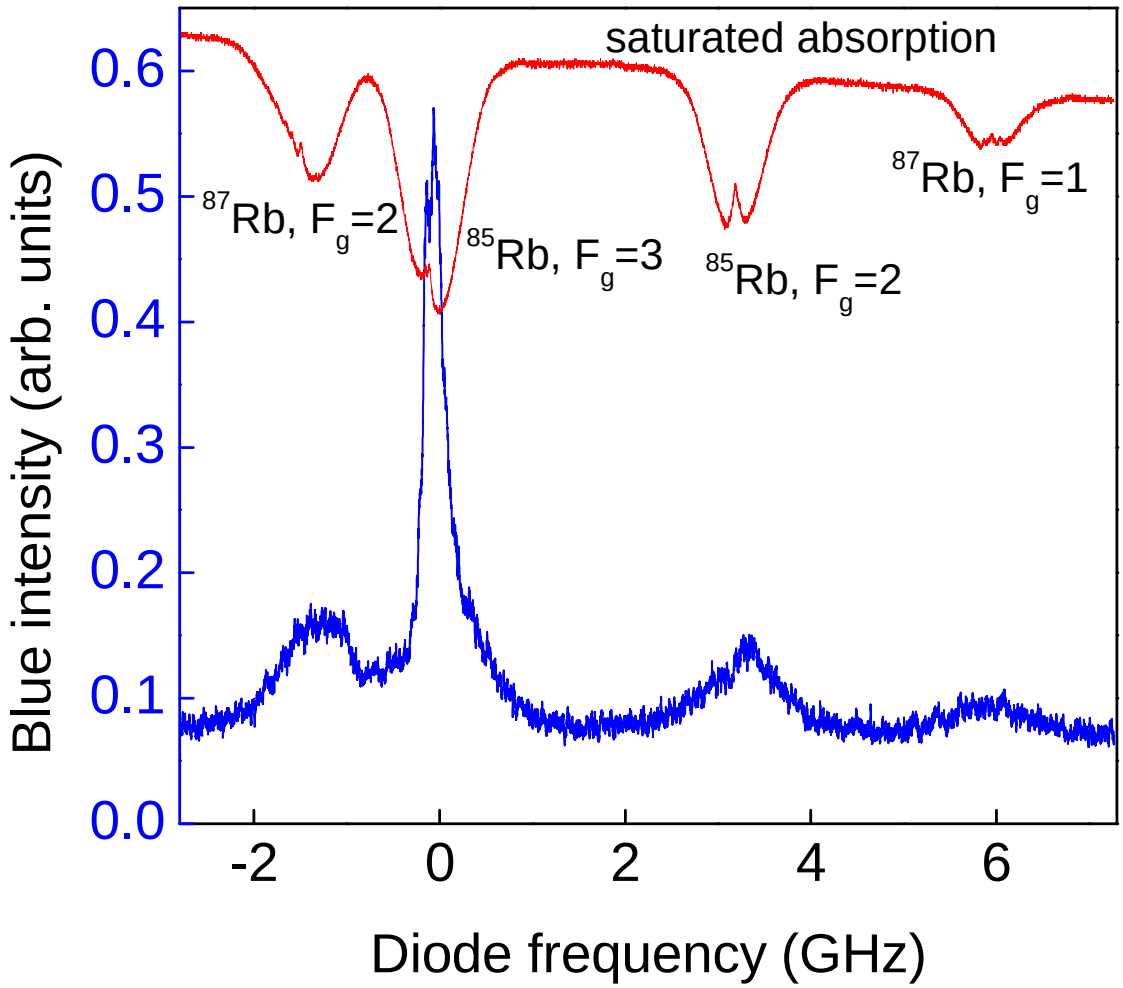

5.2 μm
(generated)
6P
776 nm
Ti:sapph
5D5/2
5P3/2
420 nm
(generated)
780 nm
Diode
5S1/2

Mesa óptica



Experimental Results

- $I_{cw} = 1.9\ \mathrm{W/cm^2}$
- $I_{fs} = 1.0\ \mathrm{mW/cm^2}$ (each mode)
- $T = 85^o\mathrm{C}$



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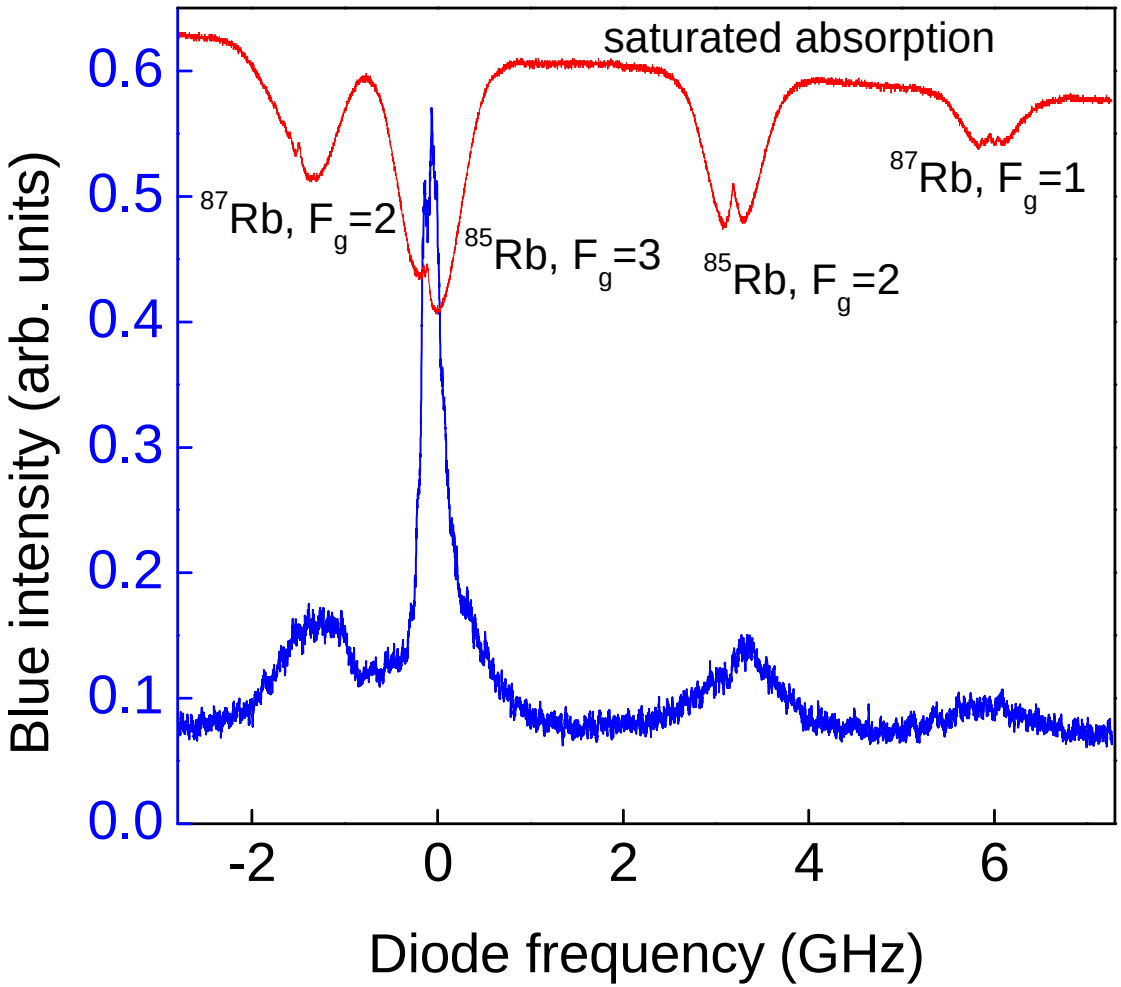

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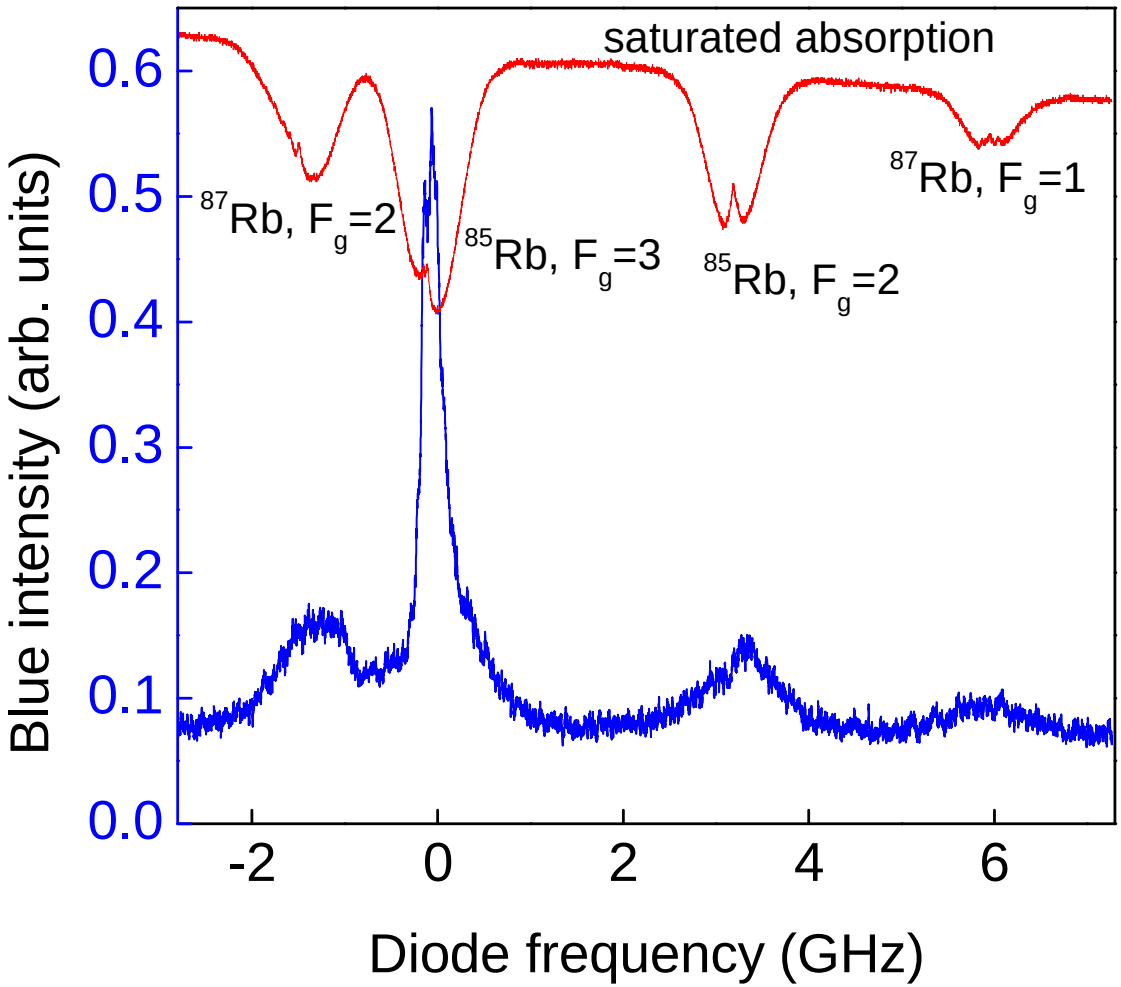
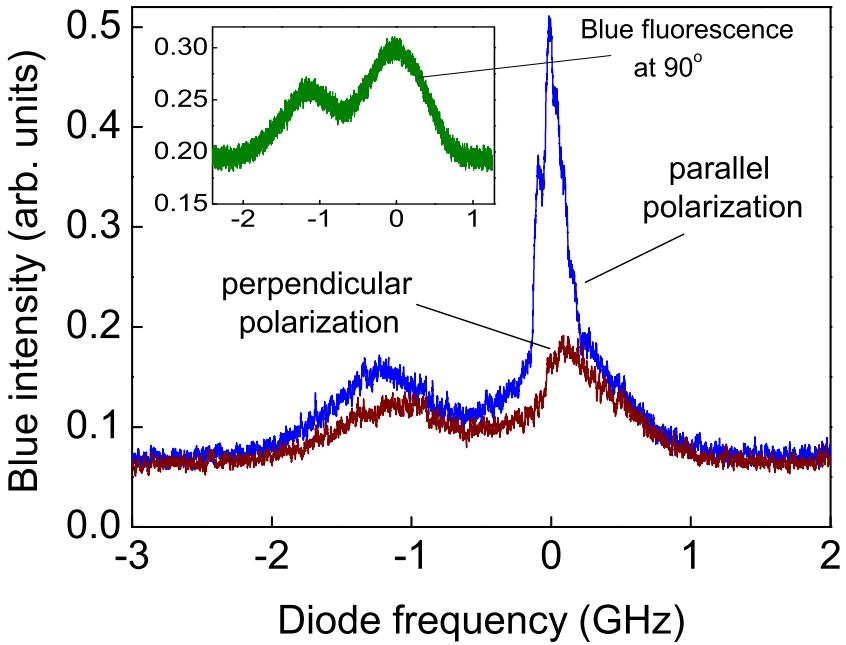
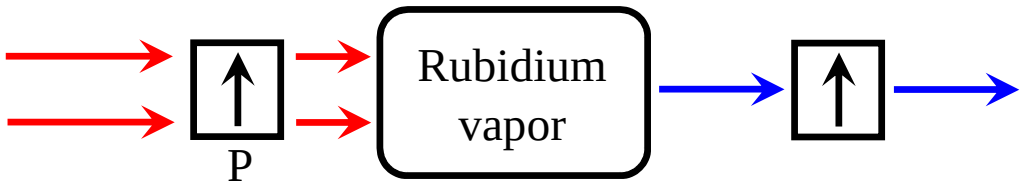
- Broad peaks: fluorescence induced by both lasers
- Flat Background: fluorescence induced by femtosecond laser



Polarization and density dependence





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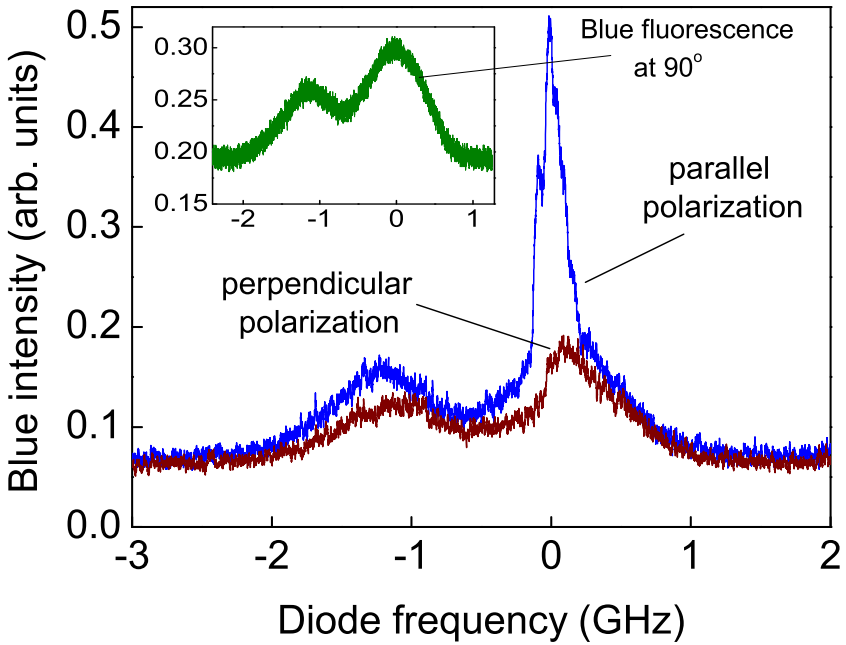

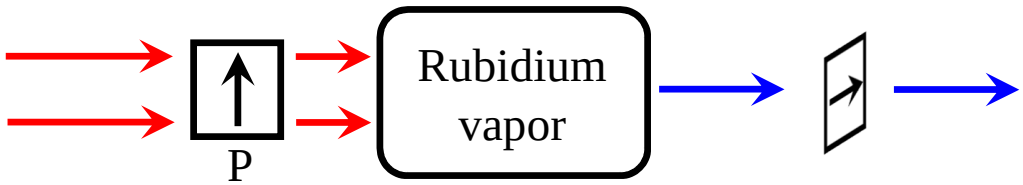

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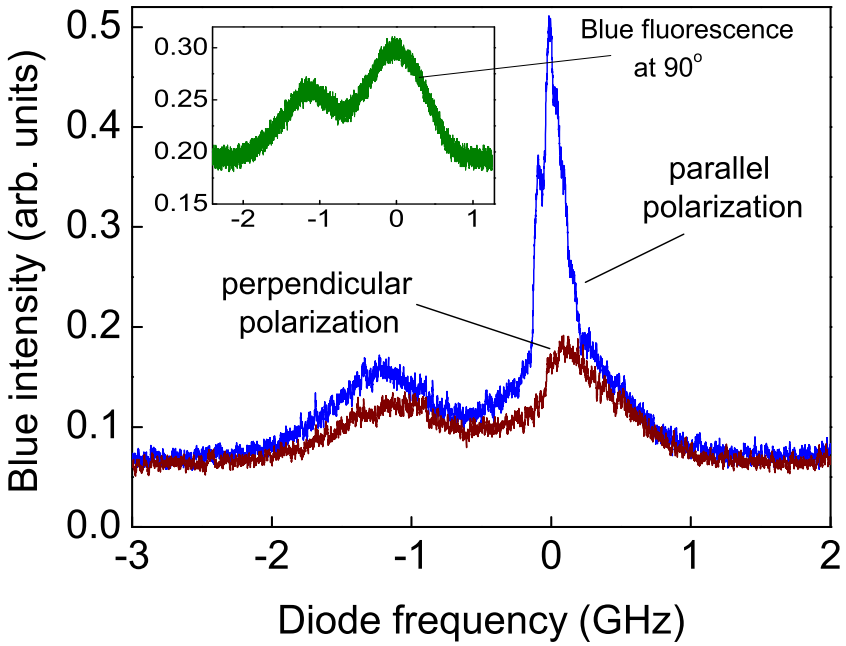

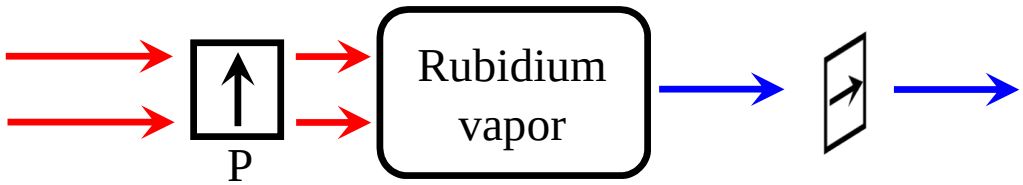

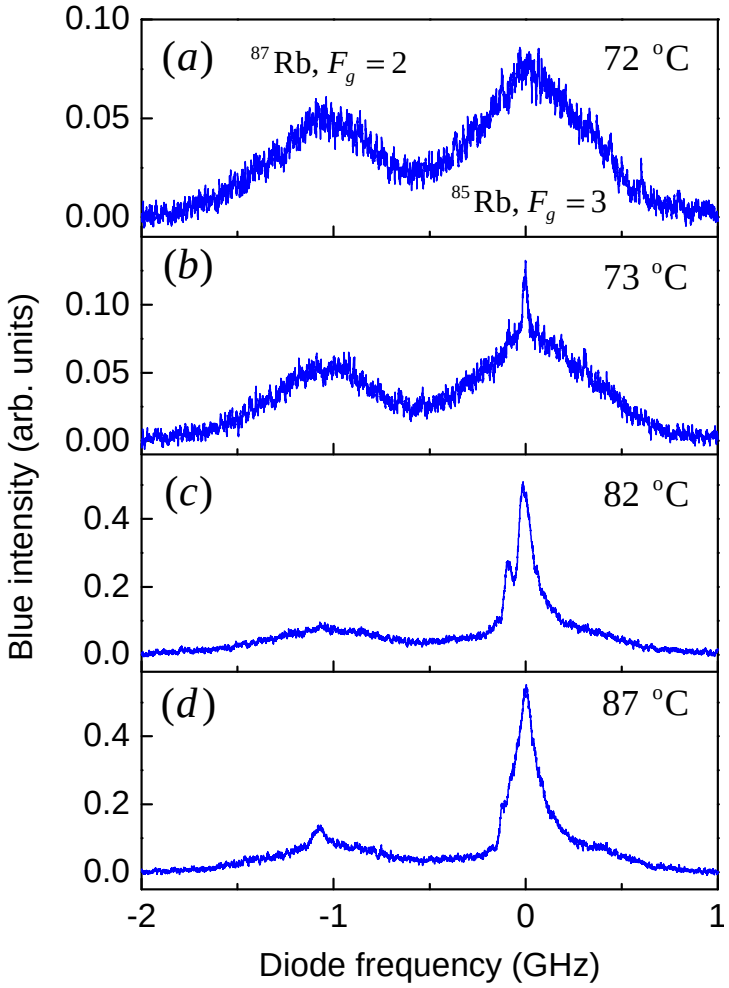

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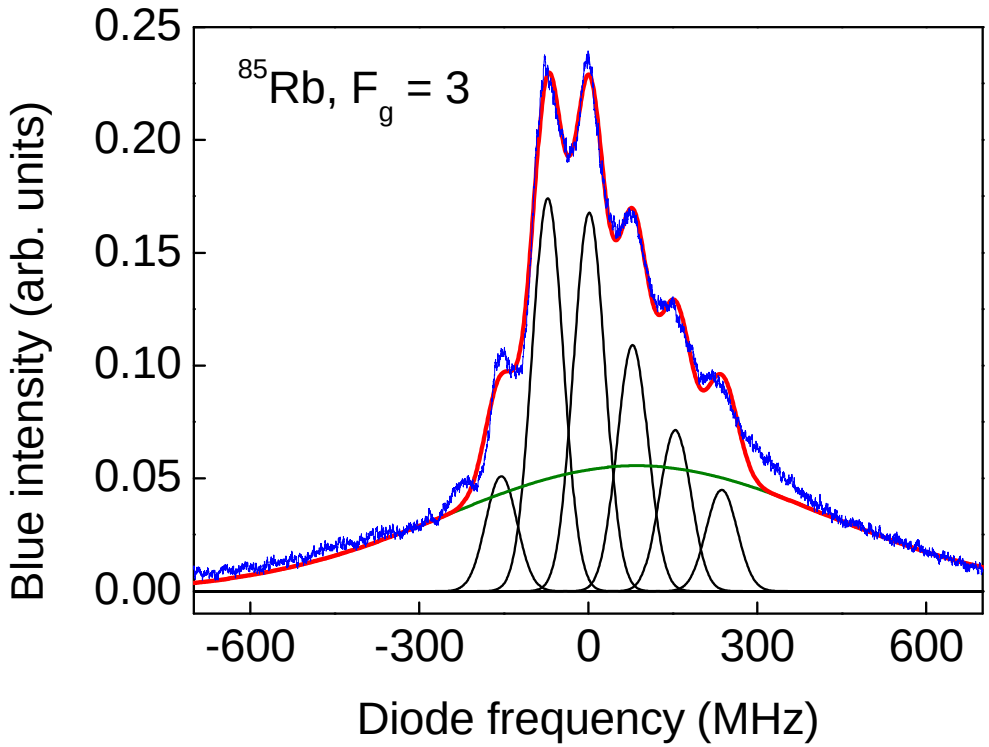
- $T = 85^{o}\mathrm{C}$
- Slow scanning
- Average of 10 measurements



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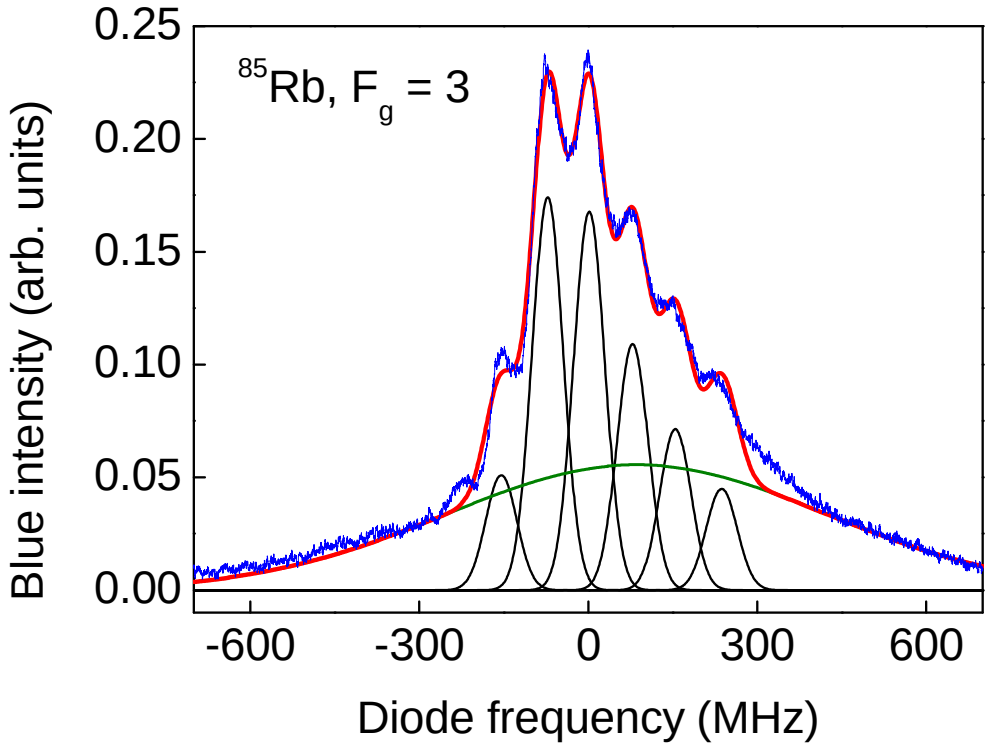

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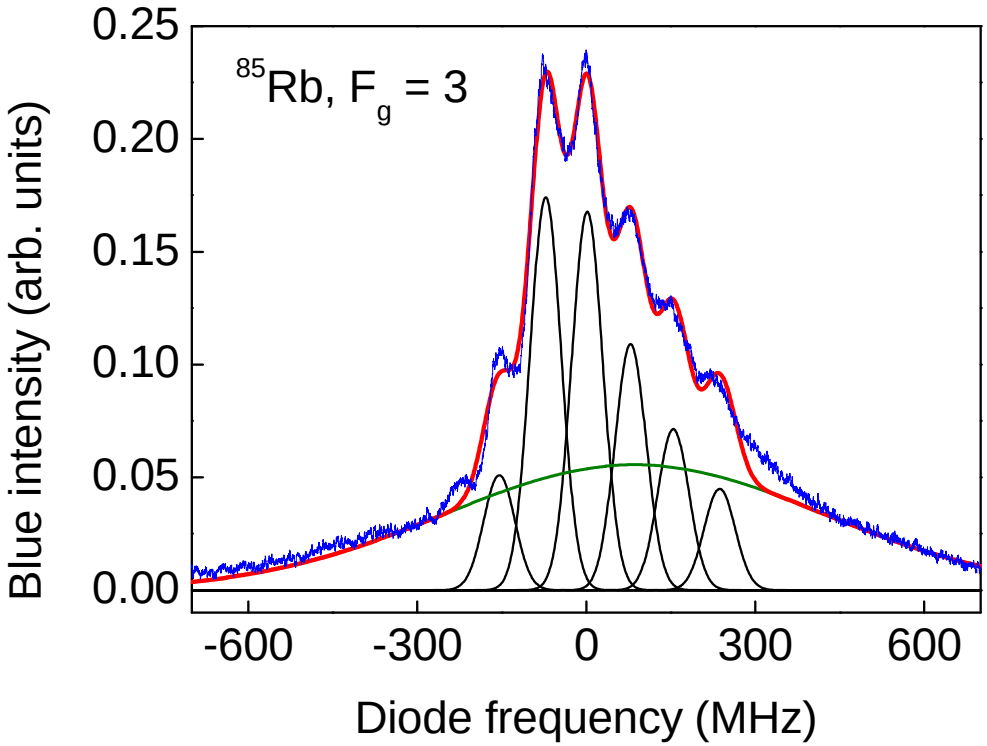
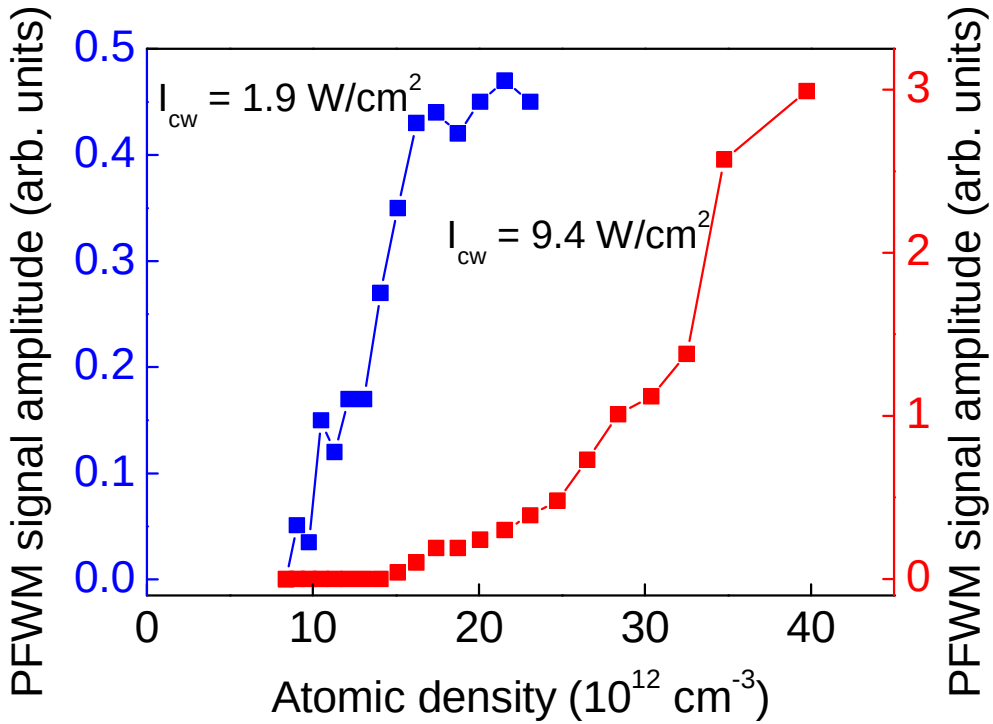
- Peak linewidths: ≈ 55 MHz
- Frequency difference between two adjacent peaks: 78 ± 4 MHz



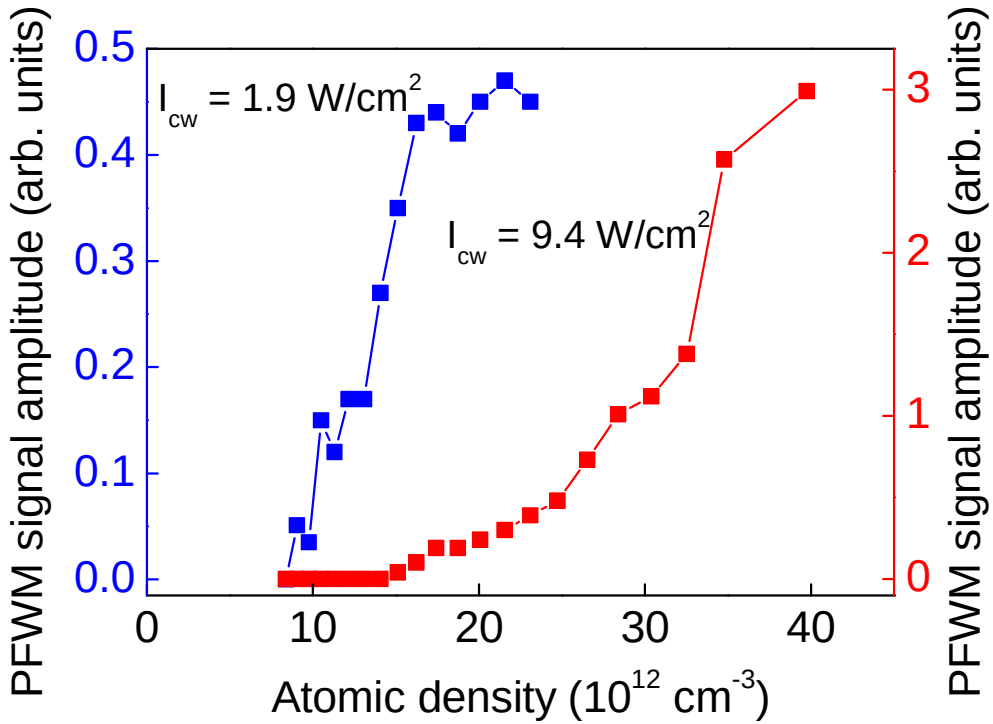
Density dependence

- Femtosecond and diode lasers in resonance with your transitions



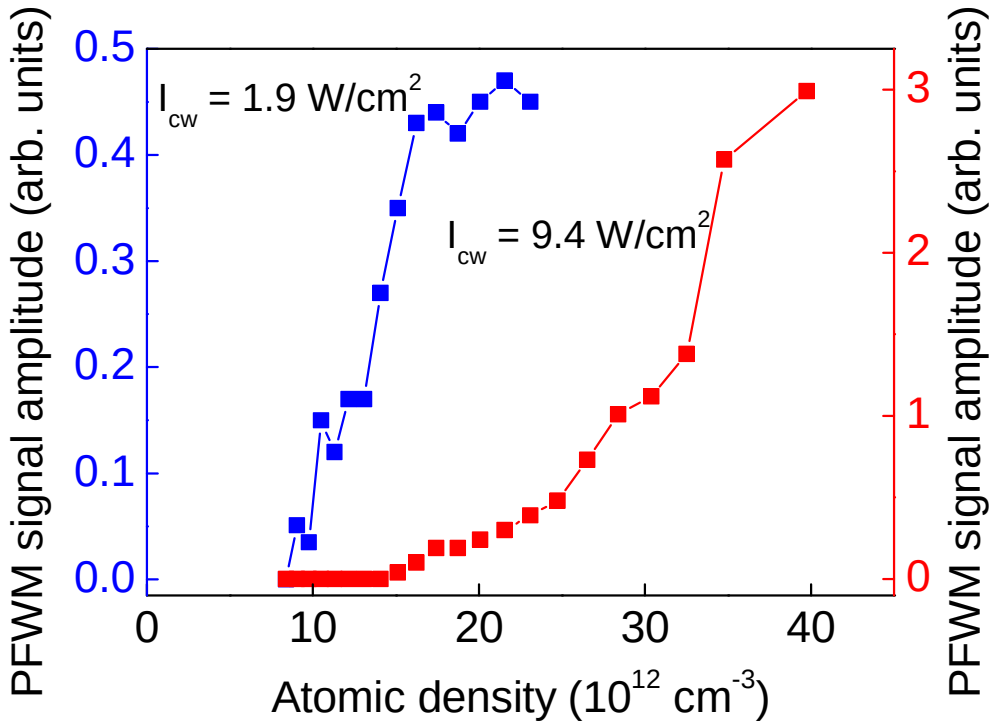
Density dependence

- Femtosecond and diode lasers in resonance with your transitions
- Exponential growth

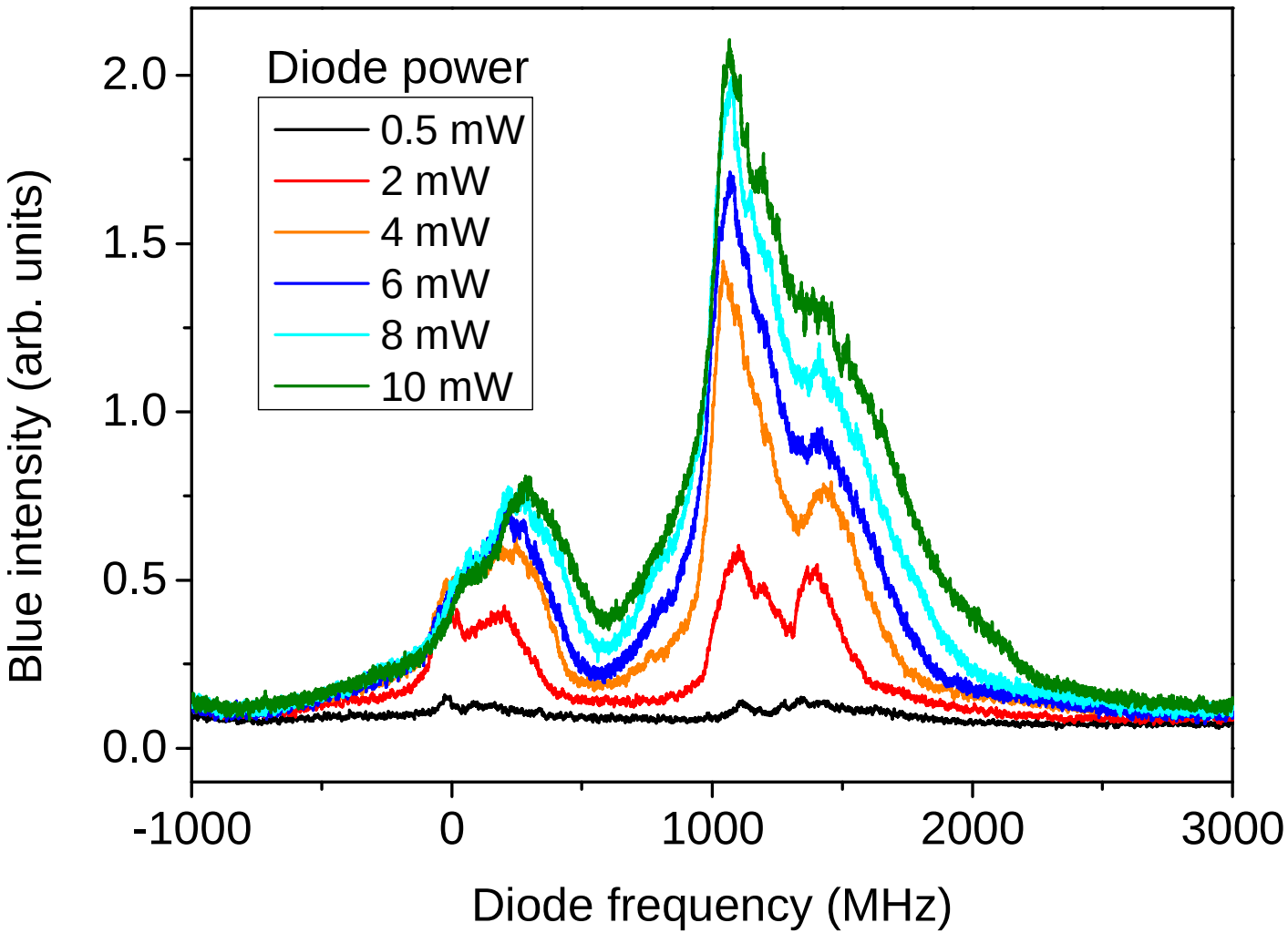


Density dependence

- Femtosecond and diode lasers in resonance with your transitions
- Exponential growth
- "Threshold" shift as a functions of the diode intensity

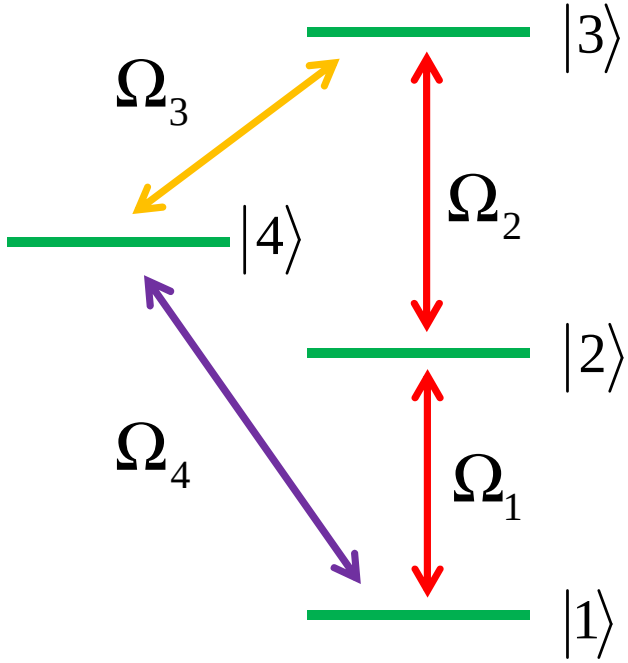


Diode intensity dependence



Theory

- Diamond-type four-level system interacting with four cw lasers.
  - Ω_1: diode laser
  - Ω_2: one mode of the femtosecond laser
  - Ω_3: seed field
  - Ω_4: blue beam generated



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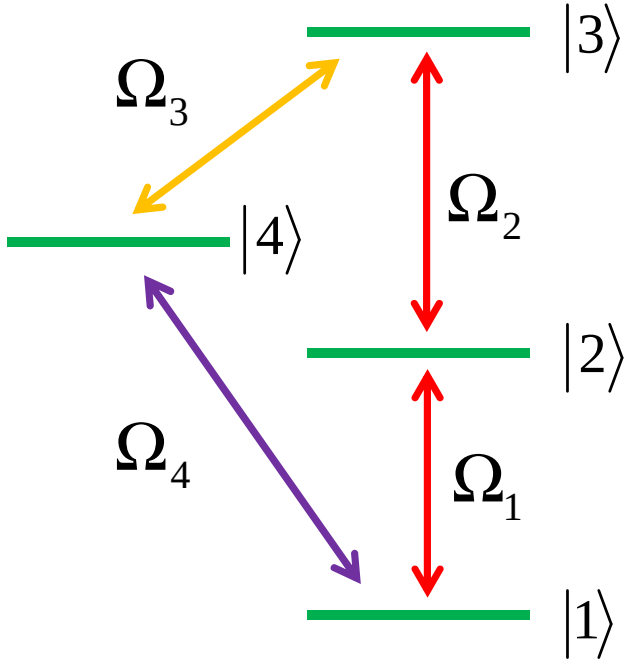
$$\hat{H}_{int} = -\hat{\mu} \cdot E$$

(Dipole electric approximation)



Maxwell-Bloch equations

$$\frac{\partial \hat{\rho}}{\partial t} = -\frac{i}{\hbar}\left[\hat{H}, \hat{\rho}\right] \qquad \text{(Liouville-Neumann)}$$

$$\frac{\partial^2 E}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P}{\partial t^2} \qquad \text{(Wave equation)}$$

$$P = N\left\langle \hat{\mu} \right\rangle \qquad \text{(Polarization)}$$

Maxwell-Bloch equations

$$\frac{\partial \rho_{jk}(z,t)}{\partial t} = -(i\omega_{jk} + \gamma_{jk})\rho_{jk}(z,t) - \frac{i}{\hbar}\langle j|\,[\hat{H}_{int}, \hat{\rho}]\,|k\rangle$$

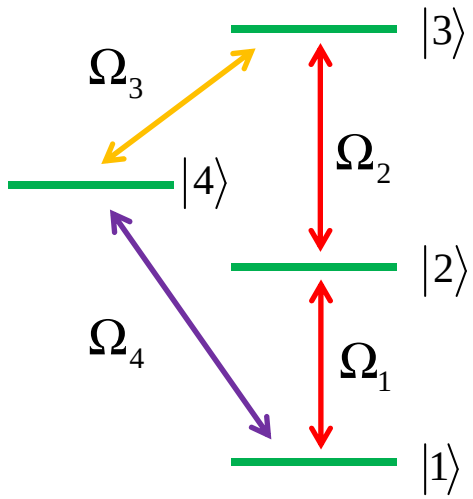
$$\frac{\partial \Omega_j(z,t)}{\partial z} = -i\alpha_{jk}\gamma_{jk}\sigma_{jk}(z,t)$$

where

$$\Omega_j = \frac{\mu_{jk}E_j^0}{\hbar} \quad \text{(Rabi frequency)}$$

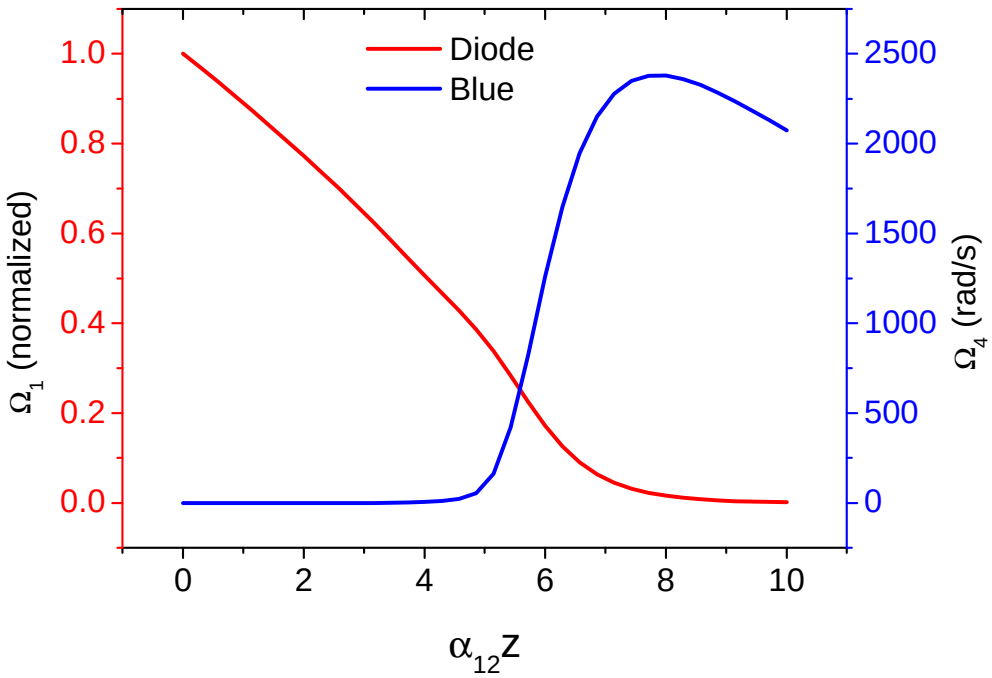
$$\alpha_{jk} = \frac{\mu_{jk}^2\omega_j}{2\hbar c\epsilon_0\gamma_{jk}}N$$

$$\sigma_{jk} = \rho_{jk}e^{-i\omega_j t}$$



Theoretical result

- Numerical solution of the equations: Runge-Kutta method
- All field at resonance
- Initial conditions: $\Omega_2 = 2.4\gamma_{33}$, $\Omega_3 = 2.4 \times 10^{-7}\gamma_{33}$ and $\Omega_4 = 0$.



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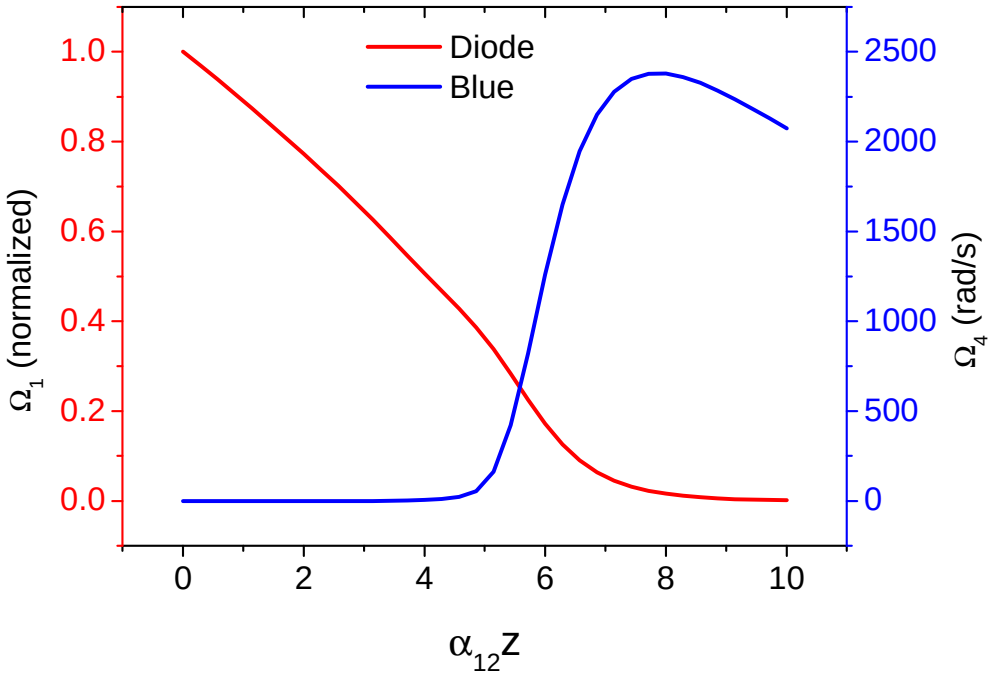

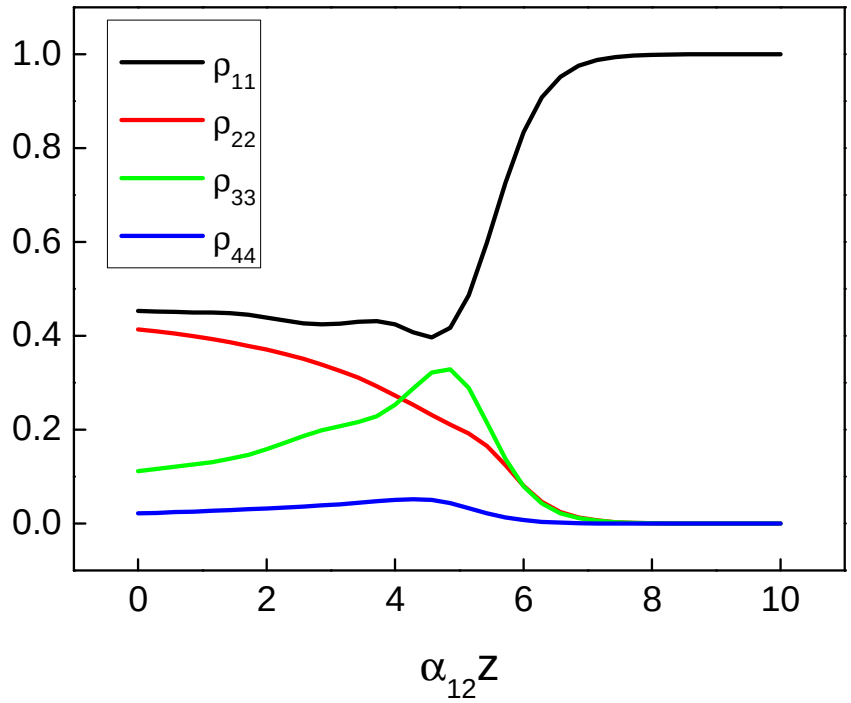

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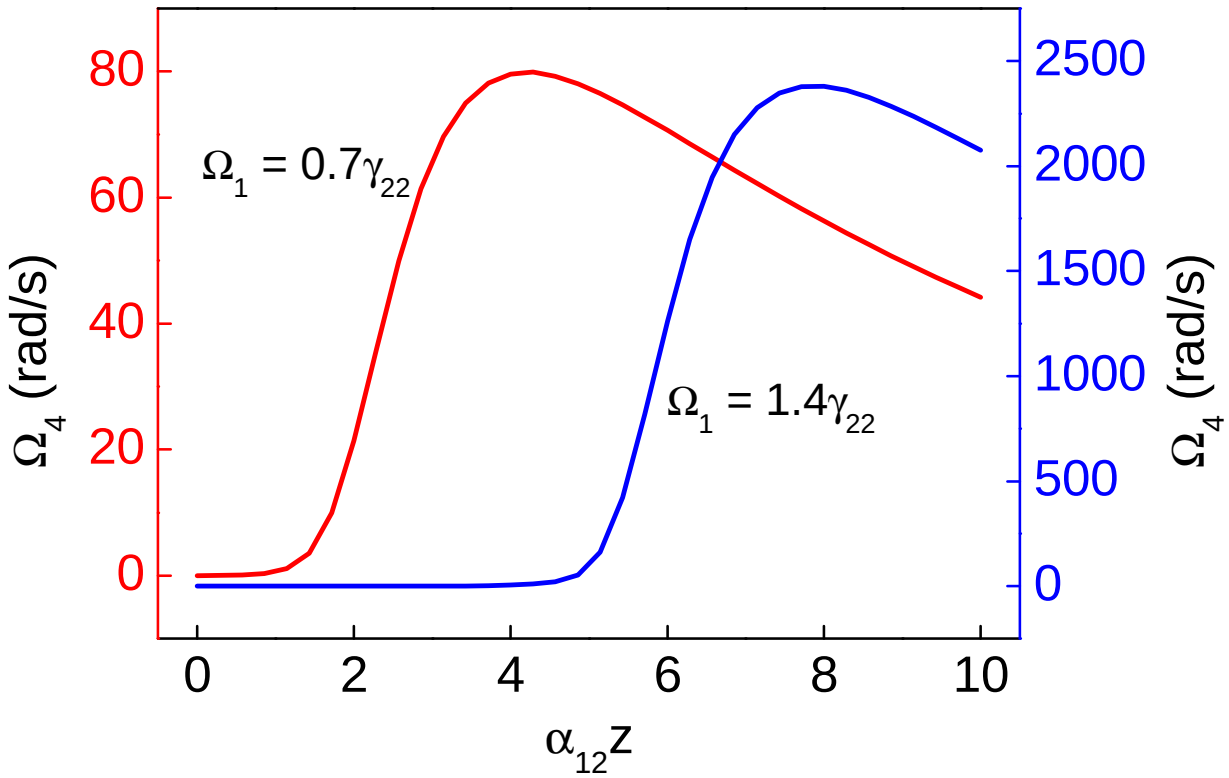

Conclusions

- We have investigated the coherent blue light generated in atomic vapor using a parametric four-wave mixing process due to the combined action of a cw laser and a train of ultrashort pulses.
- Each individual mode is responsible for inducing the nonlinear process.
- Blue signal characterization: exponential growth with saturation.
- The density dependence was theoretically modeled.
- Next step: frequency dependence modeling (with CUDA!).

CAPES

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

FACEPE
Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco

Thank you very much!