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

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The objective is to study the coherent blue light generated in rubidium vapor due to the combined action of an ultrashort pulse train and a cw diode laser.
Four-wave mixing is a nonlinear process that involves four electromagnetic waves.

\[
\mathcal{P}_4 = \epsilon_0 \chi^{(3)} E_1 E_2 E_3
\]
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In the weak interaction limit, it is a third-order process. We are interested in the generated field that is the result from the polarization that can be expressed as

\[ P_4 = \varepsilon_0 \chi^{(3)} E_1 E_2 E_3 \]
Coherent and collimated blue light generated by four-wave mixing in Rb vapour

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FWM in Rb vapor

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Experimental Results

- $I_{cw} = 1.9 \, \text{W/cm}^2$
- $I_{fs} = 1.0 \, \text{mW/cm}^2$
  (each mode)
- $T = 85^\circ \text{C}$
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- Broad peaks:
  fluorescence induced by both lasers

![Graph showing blue intensity vs. diode frequency](image-url)
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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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![Graph showing polarization and density dependence](image_url)

Blue fluorescence at 90°

Parallel polarization

Perpendicular polarization

Diode frequency (GHz)

Blue intensity (arb. units)
Experimental Results

Polarization and density dependence

Blue intensity (arb. units)

Diode frequency (GHz)

Blue fluorescence at 90°

parallel polarization

perpendicular polarization

(a) $^{87}\text{Rb}, F_g = 2$

72 °C

(b) $^{85}\text{Rb}, F_g = 3$

73 °C

(c) $\text{82 °C}$

(d) $\text{87 °C}$

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FWM in Rb vapor

Seminário de grupo
Experimental Results

- $T = 85^\circ C$
- Slow scanning
- Average of 10 measurements

**Peak linewidths:** $\approx 55$ MHz

**Frequency difference between two adjacent peaks:** $78 \pm 4$ MHz

**Graph:**
- Blue intensity (arb. units) vs. Diode frequency (MHz)
- $^{85}\text{Rb, } F_g = 3$
Experimental Results

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- $T = 85^\circ\text{C}$
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- Average of 10 measurements
- Peak linewidths: $\approx 55\ \text{MHz}$
- Frequency difference between two adjacent peaks: $78 \pm 4\ \text{MHz}$
Density dependence

- Femtosecond and diode lasers in resonance with your transitions

\[ I_{cw} = 9.4 \text{ W/cm}^2 \]

\[ I_{cw} = 1.9 \text{ W/cm}^2 \]
Density dependence

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

![Graph showing the relationship between atomic density and PFWM signal amplitude](image)
Density dependence

- Femtosecond and diode lasers in resonance with your transitions
- Exponential growth
- “Threshold” shift as a function of the diode intensity

![Graph showing the relationship between atomic density and PFWM signal amplitude. The graph has two distinct regions with different slopes, indicating the threshold behavior. Two specific values are highlighted: $I_{cw} = 1.9 \text{ W/cm}^2$ and $I_{cw} = 9.4 \text{ W/cm}^2$. The x-axis represents atomic density in units of $10^{12} \text{ cm}^{-3}$, and the y-axis represents PFWM signal amplitude in arbitrary units.]
Theory

- Diamond-type four-level system interacting with four cw lasers.
  - $\Omega_1$: diode laser
  - $\Omega_2$: one mode of the femtosecond laser
  - $\Omega_3$: seed field
  - $\Omega_4$: blue beam generated
Diamond-type four-level system interacting with four cw lasers.

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

(Dipole electric approximation)
Maxwell-Bloch equations

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

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

\[ P = N \langle \hat{\mu} \rangle \quad \text{(Polarization)} \]
Maxwell-Bloch equations

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

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

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
- All fields at resonance
- Initial conditions:
  \[ \Omega_1 = 0.7\gamma_{22}, \Omega_2 = 2.4\gamma_{33}, \Omega_3 = 2.4 \times 10^{-7}\gamma_{33} \text{ and } \Omega_4 = 0 \]
  \[ \rho_{11} = 1, \rho_{ij} = 0 \text{ for } (i,j) \neq (1,1) \]
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\[ \Omega_1 = 0.7\gamma_{22} \]
\[ \Omega_1 = 1.4\gamma_{22} \]
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.
- Many modes can be responsible for inducing the nonlinear process.
- Blue signal characterization: exponential growth with saturation.
- The density dependence was theoretically modeled.
- Next step: frequency diode dependence modeling with CUDA parallel programming (See poster P116 this afternoon).
Thank you very much!