Storing and releasing of multi-component slow light in atomic media

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Outline

1. Introduction
   - Slow light
   - Storing of slow light
   - Stationary light
2. Multi-component slow light
   - Photonic band-gap for slow light
   - Storing of multi-component slow light
3. Summary

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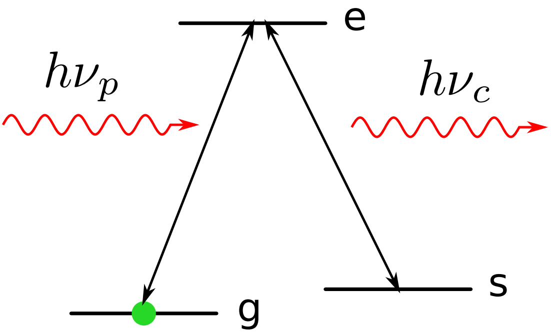
nature
£5.45 €7.59 FFr51 DM15 Lire 15000 A$16.50
www.nature.com
Cycling at the speed of light?

Three level Λ system



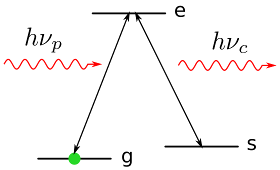
Probe beam: $\Omega_p = \mu_{ge} E_p$
Control beam: $\Omega_c = \mu_{se} E_c$

Three level Λ system

- Dark state

$$|D\rangle \sim \Omega_c|g\rangle - \Omega_p|s\rangle$$

- Transitions $g \to e$ and $s \to e$ interfere destructively
- Cancellation of absorption
- Electromagnetically induced transparency—EIT
- Very fragile
- Very narrow transparency window



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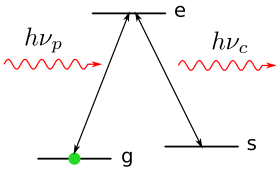

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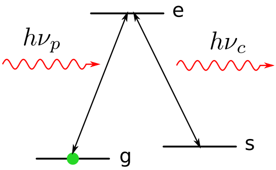

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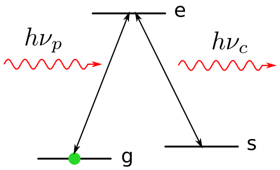

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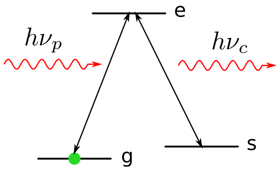

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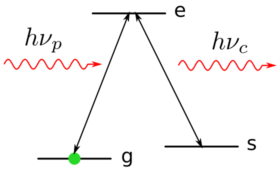
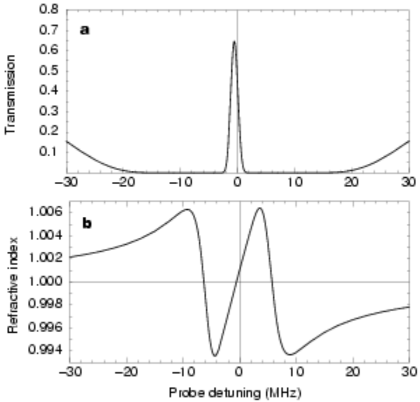


Slow light



- Narrow transparency window $\Delta\omega \sim 1\,\mathrm{MHz}$
- Very dispersive medium
- Small group velocity
  — slow light

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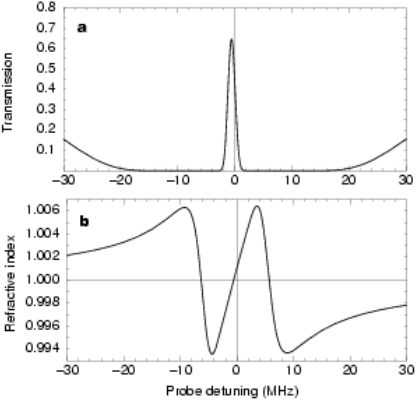

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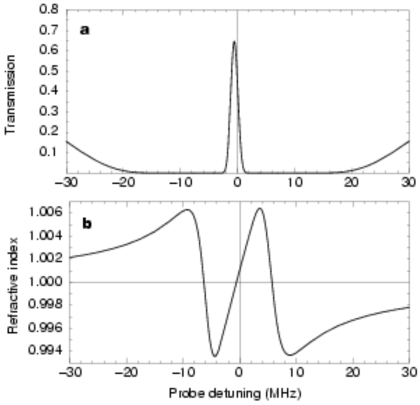

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Storing of slow light

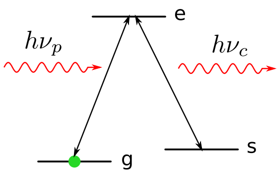
Nature, Hau *et al*, 2001

Storing of slow light

- Dark state

$$|D\rangle \sim |g\rangle - \frac{\Omega_p}{\Omega_c}|s\rangle$$

- Information on probe beam is contained in the atomic coherence
- Storing of light—switching off control beam;
  information in the atomic coherence is retained
- Releasing—switch on control beam



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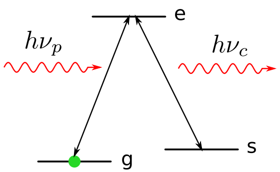

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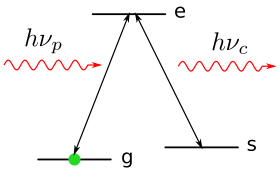

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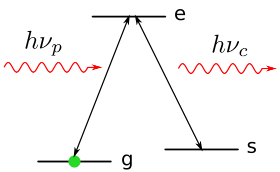

Storing of slow light

- Initial storage times (L. V. Hau *et al*, Nature 2001): 1 ms
- Recent improvement:
  - Storage time 240 ms:
    U. Schnorrberger *et al*, Phys. Rev. Lett. **103**, 033003 (2009).
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Stationary light:

Storing without switching off the control fields

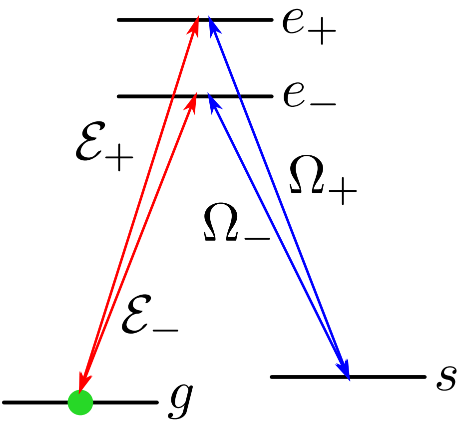
Theory:

- A. Moiseev and B. S. Ham, Phys. Rev. A **73**, 033812 (2006).
- F. E. Zimmer, J. Otterbach, R. G. Unanyan, B. W. Shore, and M. Fleischhauer, Phys. Rev. A **77**, 063823 (2008).
- M. Fleischhauer, J. Otterbach, and R. G. Unanyan, Phys. Rev. Lett. **101**, 163601 (2008).
- J. Otterbach, J. Ruseckas, R. G. Unanyan, G. Juzeliūnas, and M. Fleischhauer, Phys. Rev. Lett. **104**, 033903 (2010).

Experiment:

- Y.-W. Lin *et al.*, I. A. Yu, Phys. Rev. Lett. **102**, 213601 (2009).

Double Λ scheme



- An additional excited state
- An additional, counter-propagating control laser beam

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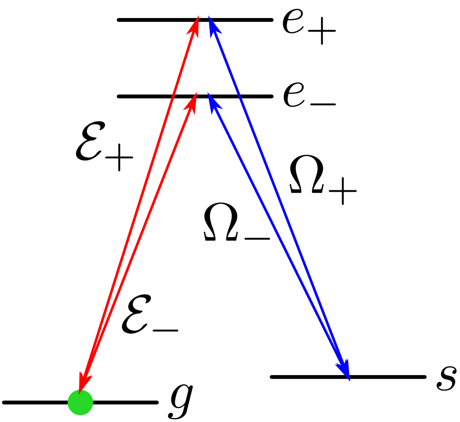

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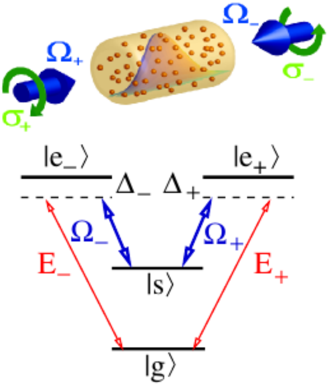

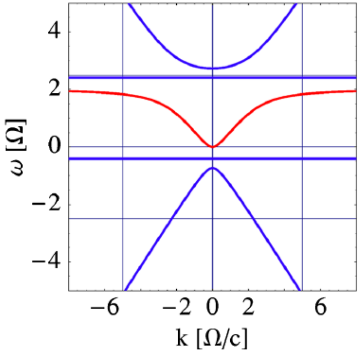

- Quadratic dispersion
- Stationary polariton (normal mode of the radiation) with non-zero m_{eff}
- Stationary light

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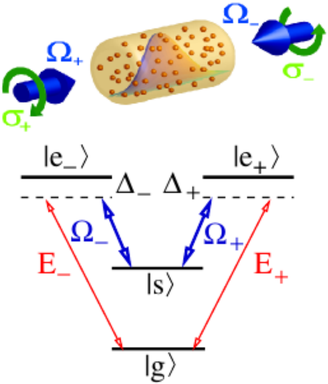

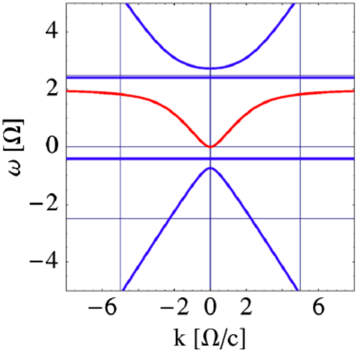

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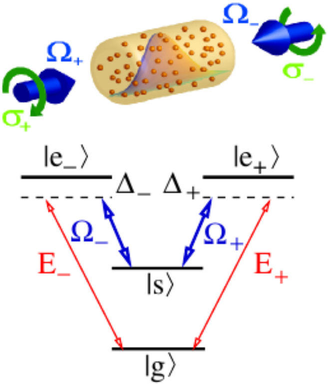

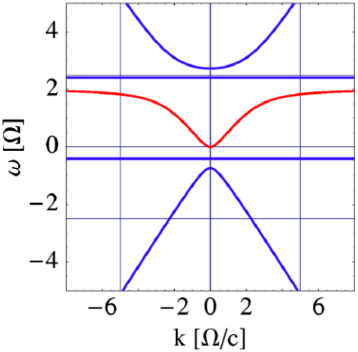

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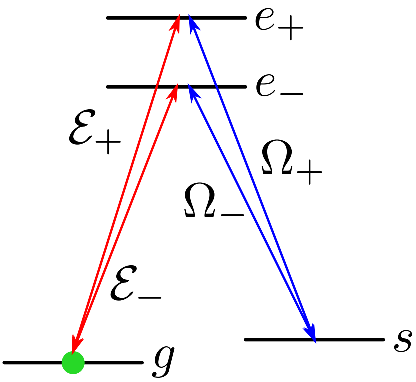
Multi-component slow light

Slow light consisting of several connected fields?

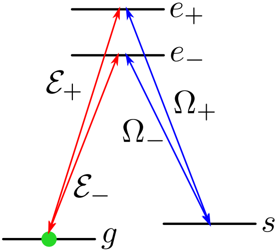
First try: double Λ scheme



Used for stationary light

Double Λ scheme: bad for our purposes

- Only one dark state can be formed
- Only one dark state polariton (propagating without absorbtion)
- For multicomponent slow light we need to add more levels.



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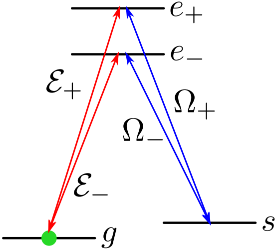

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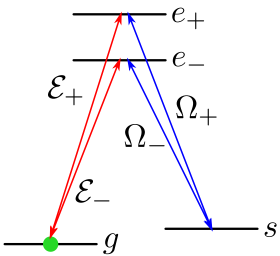

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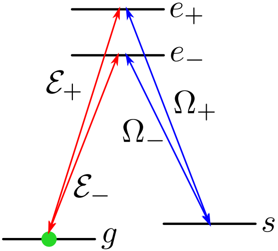
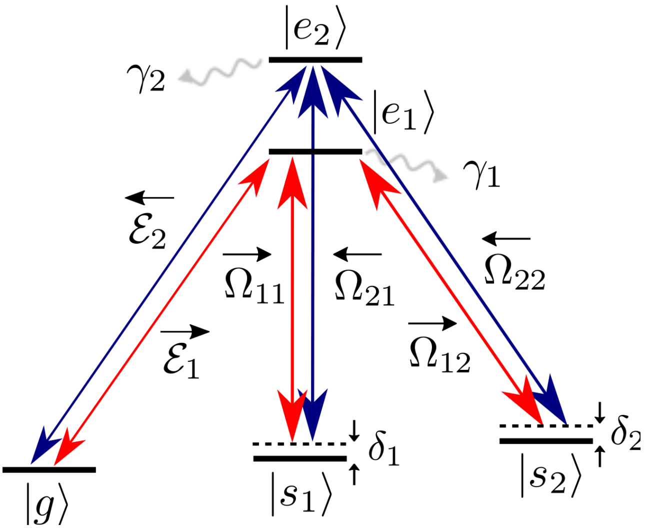


Solution

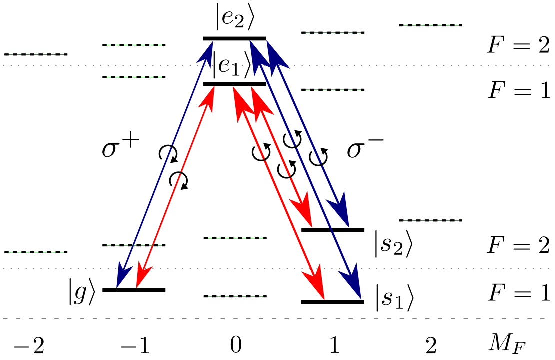
Use double tripod scheme

- R. G. Unanyan, J. Otterbach, M. Fleischhauer, J. Ruseckas, V. Kudriašov, G. Juzeliūnas, Phys. Rev. Lett. **105**, 173603 (2010).
- J. Ruseckas, V. Kudriašov, G. Juzeliūnas, R. G. Unanyan, J. Otterbach, M. Fleischhauer, Phys. Rev. A **83**, 063811 (2011).

Double tripod setup

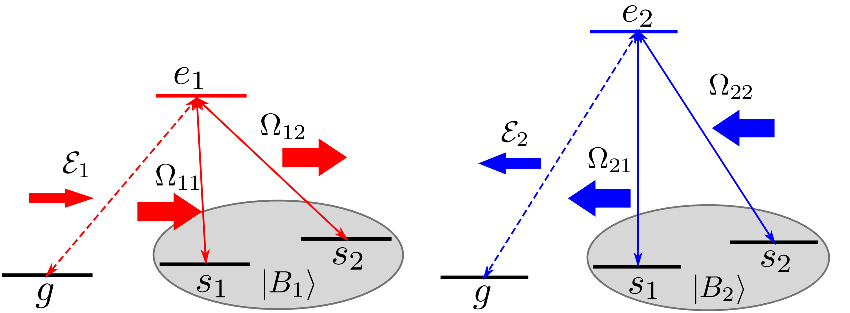


Possible experimental realization



- Atoms like rubidium or sodium.
- Transitions between the magnetic states of two hyperfine levels with $F = 1$ and 2 for the ground and excited state manifolds.
- Both probe beams are circularly σ^+ polarized, all four control beams are circularly σ^- polarized.

Double tripod setup



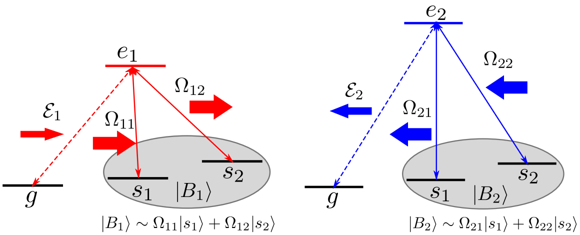
$|B_1\rangle \sim \Omega_{11}|s_1\rangle + \Omega_{12}|s_2\rangle$ $\quad$ $|B_2\rangle \sim \Omega_{21}|s_1\rangle + \Omega_{22}|s_2\rangle$

$\mathcal{E}_1$ and $\mathcal{E}_2$ drive different atomic transitions which are interconnected if $\langle B_1|B_2\rangle \neq 0$

Double tripod setup

Limiting cases:

- $\langle B_1 | B_2 \rangle = 0$ — two not connected tripods
- $\langle B_1 | B_2 \rangle = 1$ — double Lambda setup
- $0 < | \langle B_1 | B_2 \rangle | < 1$ — two connected tripods



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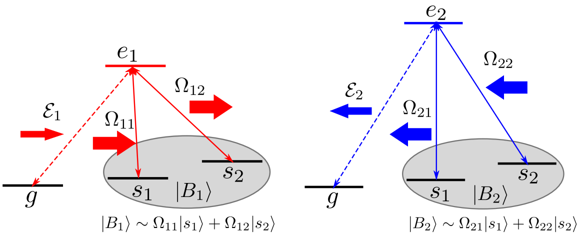

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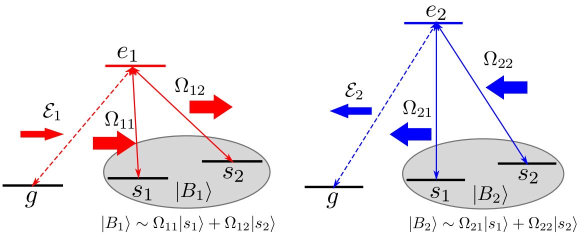

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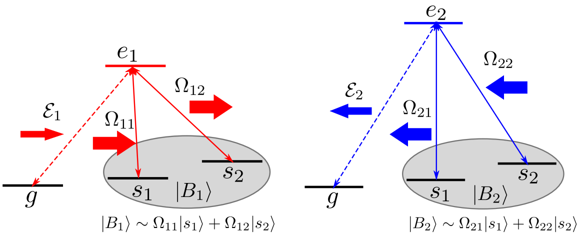

Propagation of slow light

Matrix representation — Spinor slow light:

$$\mathcal{E} = \begin{pmatrix} \mathcal{E}_1 \\ \mathcal{E}_2 \end{pmatrix}, \qquad \hat{\Omega} = \begin{pmatrix} \Omega_{11} & \Omega_{12} \\ \Omega_{21} & \Omega_{22} \end{pmatrix}, \qquad \hat{\delta} = \begin{pmatrix} \delta_1 & 0 \\ 0 & \delta_2 \end{pmatrix}$$

δ_1 and δ_2 are the detunings from two-photon resonance.

Equation for two-component probe field in the atomic cloud:

$$(c^{-1} + \hat{v}^{-1})\frac{\partial}{\partial t}\mathcal{E} - \frac{\mathrm{i}}{2k}\nabla^2\mathcal{E} - \frac{\mathrm{i}}{2}k\mathcal{E} + \mathrm{i}\hat{v}^{-1}\hat{D}\mathcal{E} = 0$$

Similar to the equation for probe field in Λ scheme, only with matrices.

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is a matrix due to two-photon detuning,

$$\hat{v}^{-1} = \frac{g^2 n}{c}(\hat{\Omega}^{\dagger})^{-1}\hat{\Omega}^{-1}$$

is a matrix of inverse group velocity (not necessarily diagonal).

Propagation of slow light

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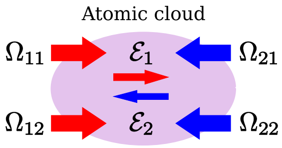
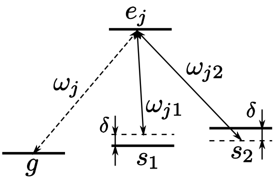
Photonic band-gap for two-component slow light

- Counter-propagating beams
- Non-zero two photon detuning
  $\delta_1 = -\delta_2 \equiv \delta \neq 0$
- Dirac type equation with non-zero mass for two component slow light:

$$\mathrm{i}\frac{\partial}{\partial t}\tilde{\mathcal{E}} = -\mathrm{i}v_0\sigma_z\frac{\partial}{\partial z}\tilde{\mathcal{E}} + \delta\sigma_y\tilde{\mathcal{E}}$$

  Here $v_0 = \frac{c\Omega^2}{g^2 n}$
- A gap in dispersion ("electron-positron" type spectrum)





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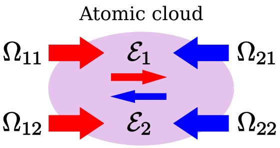

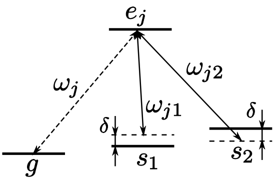

Photonic band-gap for two-component slow light

- Counter-propagating beams
- Non-zero two photon detuning
  $\delta_1 = -\delta_2 \equiv \delta \neq 0$
- Dirac type equation with non-zero mass for two component slow light:

$$\mathrm{i}\frac{\partial}{\partial t}\tilde{\mathcal{E}} = -\mathrm{i}v_0\sigma_z\frac{\partial}{\partial z}\tilde{\mathcal{E}} + \delta\sigma_y\tilde{\mathcal{E}}$$

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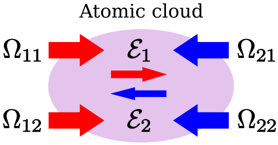

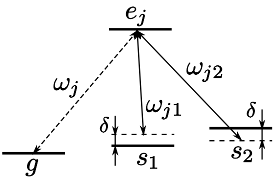

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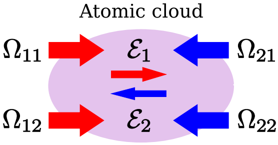

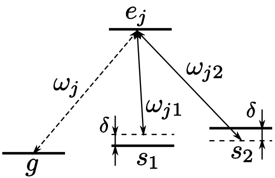

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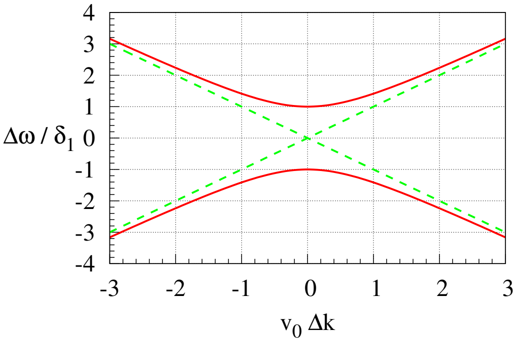

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  $\Delta\omega^{\pm} = \pm\sqrt{v_0^2 \Delta k^2 + \delta^2}$
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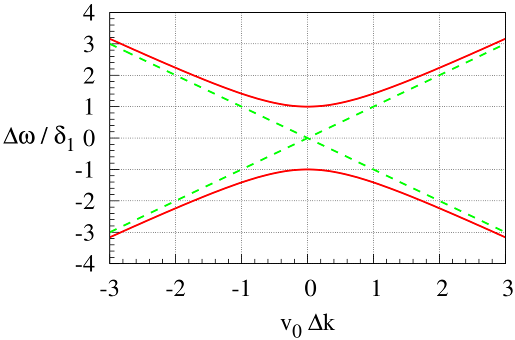

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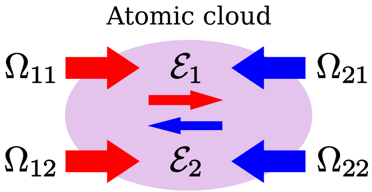
Multi-component stationary light

How to create multi-component stationary light?

- Configuration with counter-propagating beams.
- Initially two-photon detuning δ is zero
- and only one probe beam $\mathcal{E}_1$ with central frequency $\Delta\omega = 0$ is incident on the atomic cloud
- resulting in slow light, propagating with the velocity v_0



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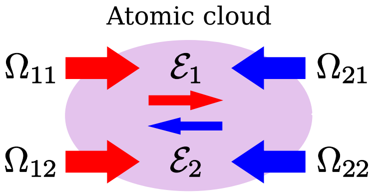

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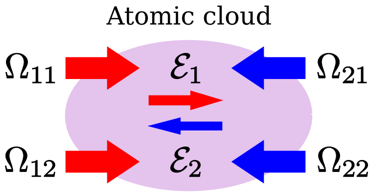

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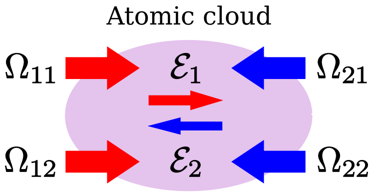

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- When the wave packet of the beam $\mathcal{E}_1$ is inside the cloud, the two-photon detuning is suddenly increased from 0 to δ
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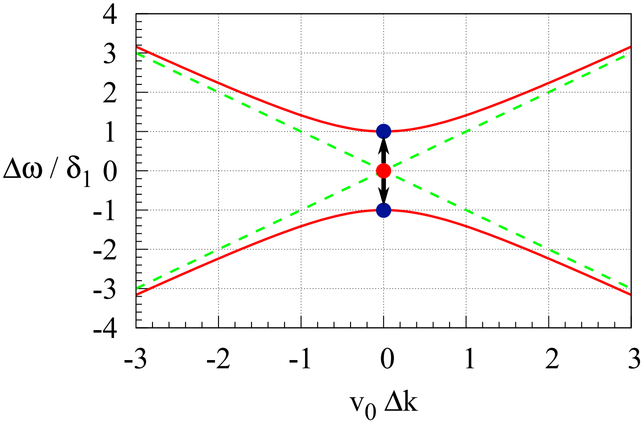

Light is converted to superposition of eigenstates with positive and negative frequencies.

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$$\begin{pmatrix} \mathcal{E}_1 \\ \mathcal{E}_2 \end{pmatrix} = \begin{pmatrix} \cos(\delta t) \\ \sin(\delta t) \end{pmatrix}$$

- At later time $t = t_r$, decreasing the two-photon detuning δ back to zero, the stationary light is converted back to slow light

Probe beam can be frozen in the medium forming a two-component stationary light and subsequently released.

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Differences from storing of slow light in atomic medium:

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Limiting factors

- Spreading of the wave packet due to parabolic dispersion. Time to double the width

$$t_{\mathrm{d}} = \frac{\sqrt{3}\delta}{2\sigma_{\omega}^{2}}$$

- Diffusion due to non-adiabatic terms. Diffusion coefficient is $L_{\mathrm{abs}} v_0$. Time to double the width

$$t_{\mathrm{d}} = \frac{3 v_0}{4 L_{\mathrm{abs}} \sigma_{\omega}^{2}}$$

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Thank you for your attention!