Multicomponent Slow Light

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Abstract

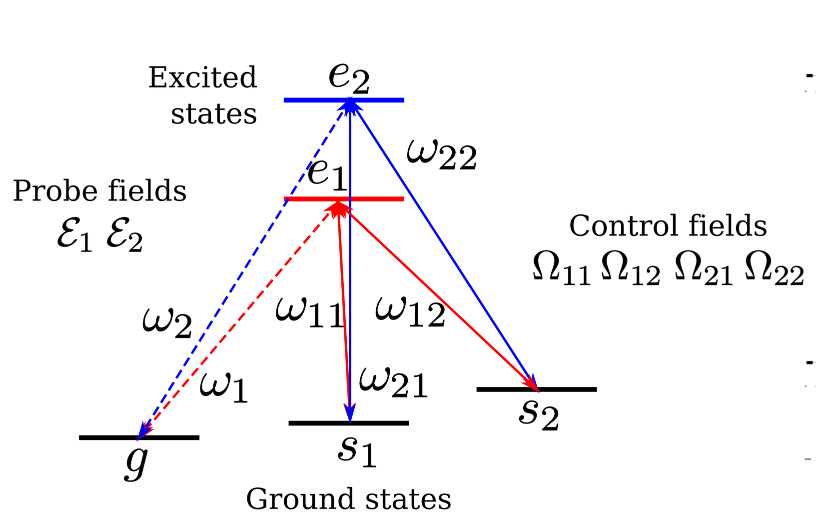
We study the propagation of two weak probe fields of light in an atomic ensemble coherently driven by two pairs of control laser fields in a double tripod-type setup. The probe fields "dressed" by the atomic medium form quasi-particles termed spinor slow light polaritons (SSPs). The SSPs represent a two-component field which is shown to obey under certain conditions a relativistic equation of the Dirac-type. The polaritons posses an "effective speed of light" given by the group-velocity of slow-light, and can be made massive by inducing a small two-photon detuning. This leads to formation of the "particle-antiparticle" dispersion branches separated by a gap. The corresponding effective Compton length determines the tunneling length of the probe light through the band-gap along the sample. We also investigate to exchange the optical vortex between the control and probe fields using the double tripod scheme.

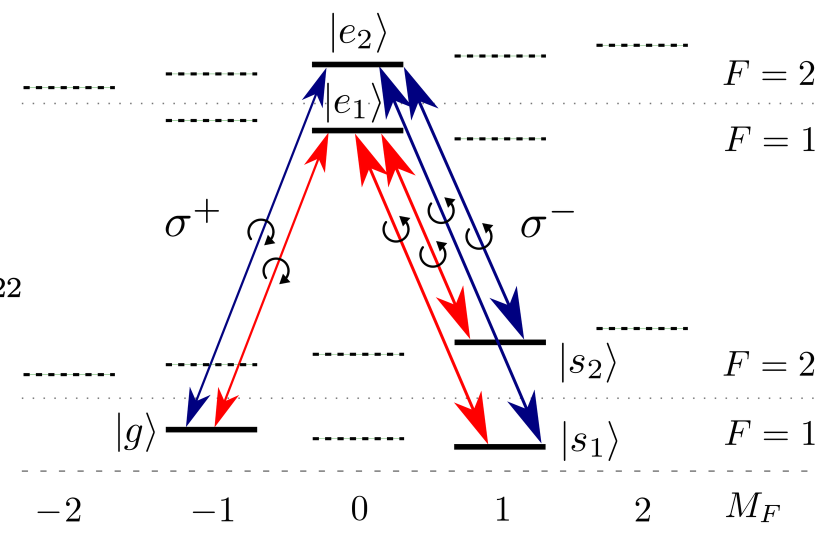
1. R. G. Unanyan, J. Otterbach, M. Fleischhauer, J. Ruseckas, V. Kudriašov, and G. Juzeliūnas, Phys. Rev. Lett. **105**, 173603 (2010).
2. J. Ruseckas, V. Kudriašov, G. Juzeliūnas, R. G. Unanyan, J. Otterbach, and M. Fleischhauer, Phys. Rev. A **83**, 063811 (2011).

Double-tripod linkage pattern

Conditions:

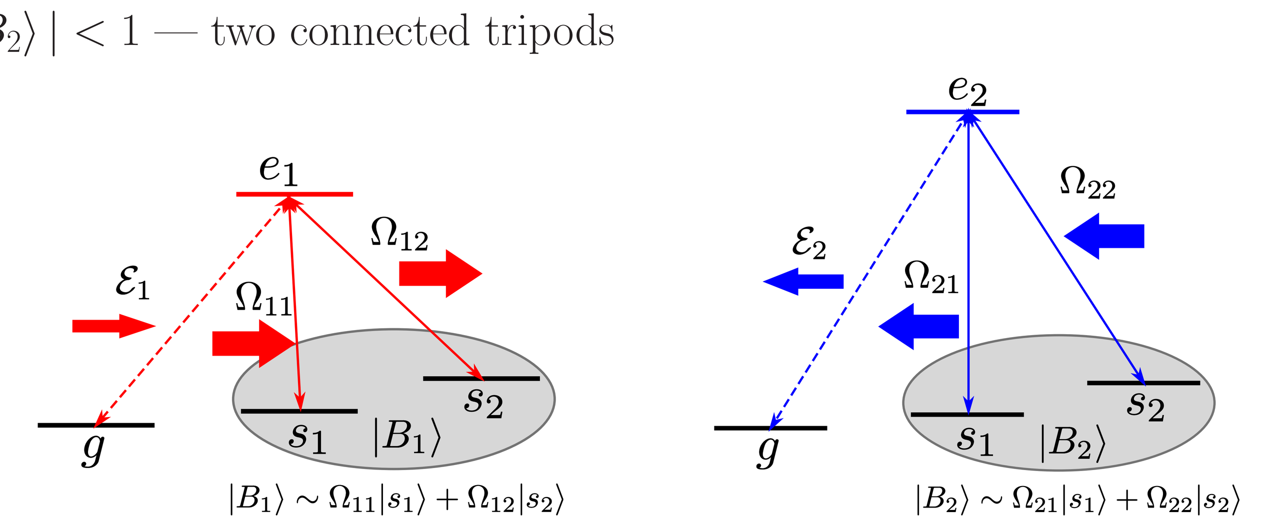
- Propagation of two weak (probe) light beams in a resonant atomic medium under the influence of several stronger (control) laser beams.
- Probe beams couple the ground state g to two excited states e_1 and e_2 .
- Control beams couple excited states e_j to another two ground states s_k .
- Control beams make the medium transparent for resonant probe beams in a narrow frequency range due to the electromagnetically induced transparency (EIT).
- 4-photon resonance: $\omega_1 - \omega_{11} = \omega_2 - \omega_{21}$, $\omega_1 - \omega_{12} = \omega_2 - \omega_{22}$.





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



Description

Matrix representation — spinor slow light:

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

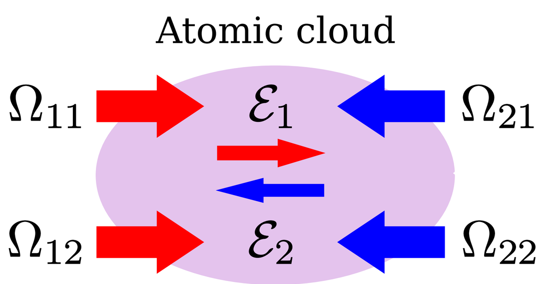
δ_1 and δ_2 are the detunings from two-photon resonance.
Matrix equation for the two-component probe field (for counter-propagating control fields):

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

Similar to the equation for probe field in Λ scheme, only with matrices.
$\hat{D} = \hat{\Omega}\hat{\delta}\hat{\Omega}^{-1}$ — matrix of the two-photon detuning

$v^{-1} = \frac{g^2 n}{c}(\hat{\Omega}^\dagger)^{-1}\hat{\Omega}^{-1}$ — defines matrix of inverse group velocity;

g is the coupling strength, n is the atom number density.



- The group velocity is a non-diagonal matrix
- Individual probe fields do not have a definite group velocity
- Only special combinations of both probe fields (polaritons) propagate in the atomic cloud with the definite velocities

The Rabi frequencies of control beams with equal intensities: $\Omega_{ij} = \frac{\Omega}{\sqrt{2}}\exp(iS_{ij})$
The relative phase of the control fields: $S = \frac{1}{2}(S_{12} + S_{21} - S_{11} - S_{22})$

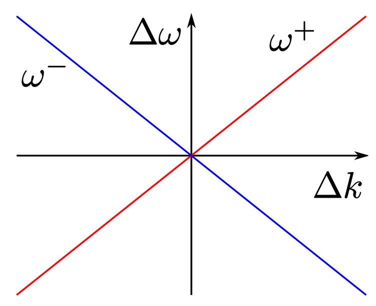
- $S = \pm\pi/2$ — two not connected tripods
- $S = 0$ — double Lambda setup
- $0 < |S| < \pi/2$ — two connected tripods

Matrix of inverse polariton velocity: $\sigma_z v^{-1} = \frac{1}{v_0}\frac{1}{\sin^2 S}\begin{pmatrix} 1 & -\cos S \\ \cos S & -1 \end{pmatrix}$, $v_0 = \frac{c\Omega^2}{g^2 n}$

Neutrino type oscillations for polaritons

Zero two-photon detuning $\delta_1 = \delta_2 = 0$

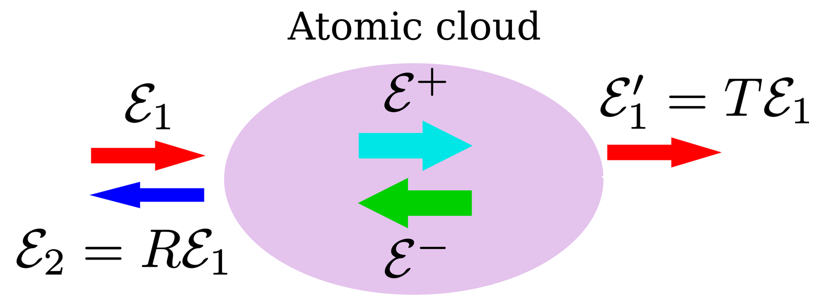
$$\sigma_z \tilde{v}^{-1}\frac{\partial}{\partial t}\tilde{\mathcal{E}} + \frac{\partial}{\partial z}\tilde{\mathcal{E}} = 0$$

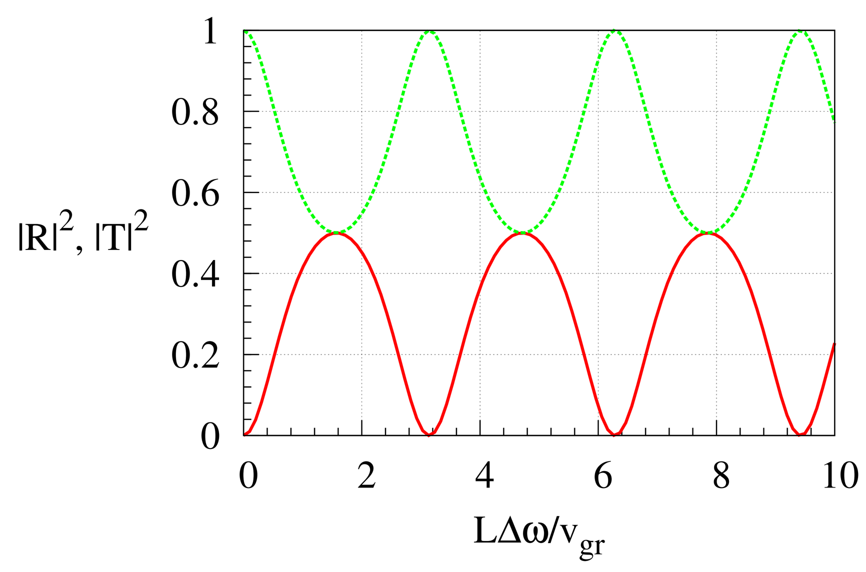


Two polaritons $\tilde{\mathcal{E}}^\pm$. Two dispersion branches with opposite slopes: $\Delta\omega^\pm = \pm v_{\rm gr}\Delta k$. Here $\Delta\omega = 0$ is the intersection point of both polariton branches.
$\mathcal{E}_1$ is reflected into $\mathcal{E}_2$. Reflection and transmission coefficients:

$$R = \frac{-2i\cos(S)\sin(\Delta\omega L/v_{\rm gr})}{(1-|\sin S|)e^{-i\Delta\omega\frac{L}{v_{\rm gr}}} - (1+|\sin S|)e^{i\Delta\omega\frac{L}{v_{\rm gr}}}}, \quad T = \frac{2|\sin S|}{(1+|\sin S|)e^{i\Delta\omega\frac{L}{v_{\rm gr}}} - (1-|\sin S|)e^{-i\Delta\omega\frac{L}{v_{\rm gr}}}}$$

Oscillations of R and T occur if $|S| \neq \pi/2$ i.e. if we have two connected tripod systems



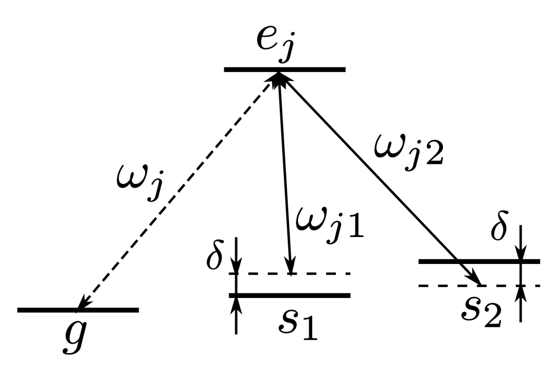


Dirac equation for two-component polariton

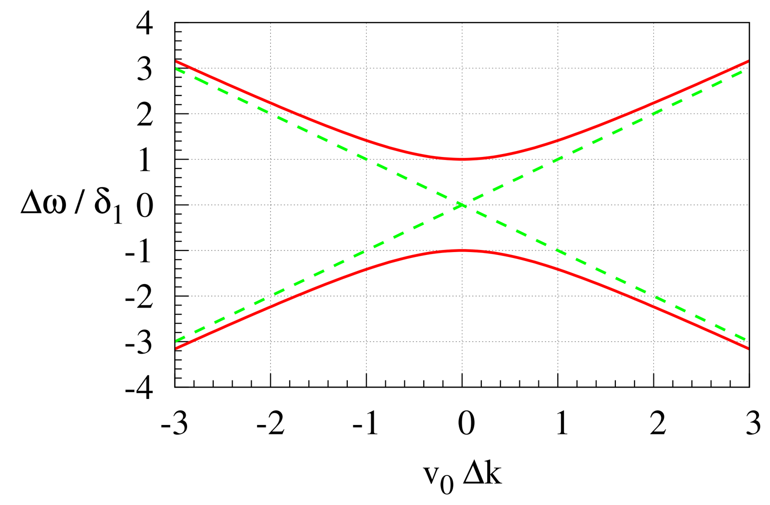
We assume that $S = \pm\pi/2$. Non-zero two photon detuning $\delta_1 = -\delta_2 \equiv \delta \neq 0$

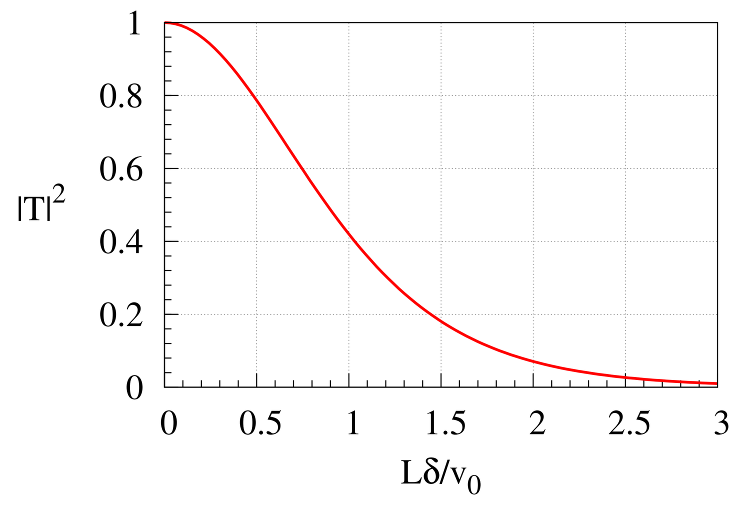
- A gap in dispersion ("electron-positron" type spectrum)
- Dirac type equation with non-zero mass for two component polaritons:

$$i\frac{\partial}{\partial t}\tilde{\mathcal{E}} = -iv_0\sigma_z\frac{\partial}{\partial z}\tilde{\mathcal{E}} + \delta\sigma_y\tilde{\mathcal{E}}$$



Relativistic particle-antiparticle dispersion: $\Delta\omega^\pm = \pm\sqrt{v_0^2\Delta k^2 + \delta^2}$
$\hbar\delta = mv_0^2$ — gap width, m — polariton effective mass





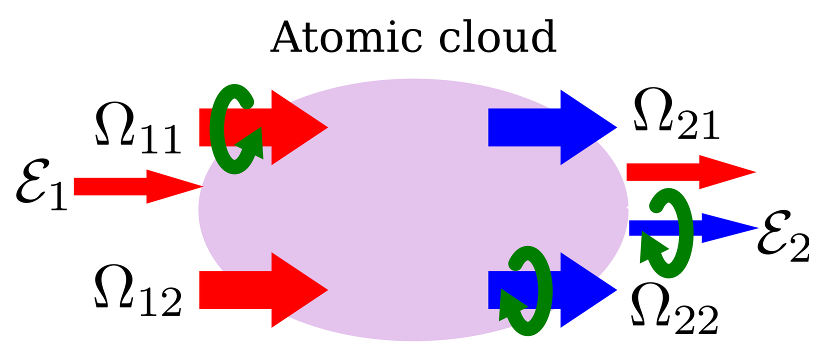
Reflection and transmission coefficients at the gap center ($\Delta\omega = 0$):

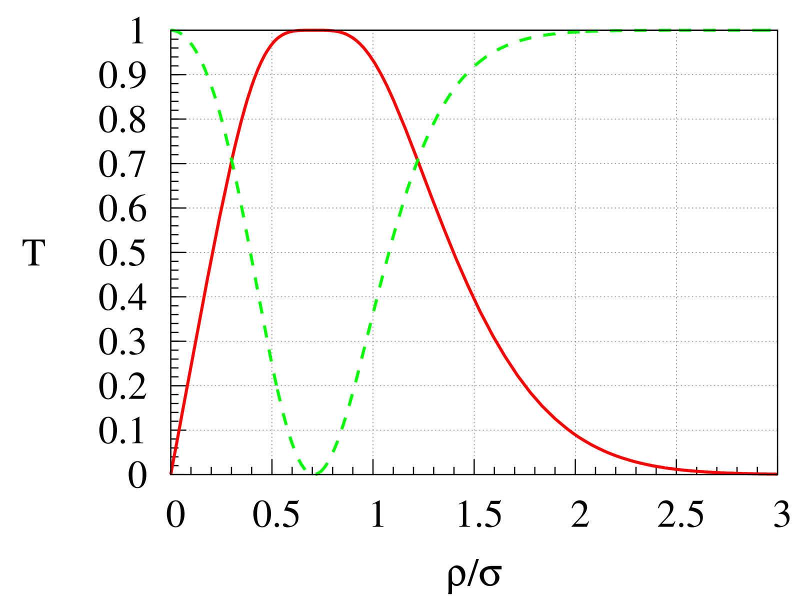
$$T = \cosh^{-1}(L/\lambda_C), \quad R = \tanh(L/\lambda_C)$$

$\lambda_C = \hbar/mv_0 = v_0/\delta$ — Compton wave-length of the polariton. The Compton wave-length determines the polariton tunneling length.

Transfer of optical vortex to probe beams

- Co-propagating probe beams
- Control beams with Rabi frequencies $\Omega_{11} \sim e^{i\ell\varphi}$ and $\Omega_{22} \sim e^{-i\ell\varphi}$ have optical vortices with opposite vorticity
- Incident field $\mathcal{E}_1$ is without vortex
- Probe field $\mathcal{E}_2$ acquires an optical vortex





Conclusions

- The spinor slow light in atomic medium obeys an effective Dirac equation for a massive particle.
- By changing the two-photon detuning the medium can act as a photonic crystal with a controllable band-gap.
- If the frequency of the incoming probe light is within the band-gap, the light tunnels through the sample. The tunneling length is given by the effective Compton wave-length of the SSP.
- For frequencies of the incoming light outside the band-gap, the reflection and transmission coefficients exhibit an oscillatory dependence on the two-photon detuning and the sample length. This can be interpreted as a mirrorless frequency filter.

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