Electromagnetically-Induced Transparency with Classical and Nonclassical Light

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Abstract: We present our progress towards storage of squeezed light by means of electromagnetically-induced transparency as well as a family of protocols for routing, frequency conversion, and geometric steering of optical modes in atomic systems with multiple excited levels.

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1. Raman adiabatic transfer of optical states in multilevel atoms

Frequency conversion and routing of quantum information carried by light is of great importance for future quantum communication networks. We demonstrate a protocol called Raman adiabatic transfer of optical states (RATOS), which allows the transfer and distribution of a quantum state of light between different optical modes in an adiabatic and thus robust way. RATOS is based on electromagnetically-induced transparency (EIT) in a medium with multiple excited levels (multiple-Λ system).

As shown in [1], a double- Λ system coupled by two signal fields (described by annihilation operators $\hat{a}_1$ and $\hat{a}_2$) and two strong control fields (described by their Rabi frequencies Ω_1 and Ω_2) exhibits EIT for the following superposition $\hat{b}$ of the signal fields:

$$\hat{b} \propto \frac{\Omega_1}{g_1}\hat{a}_1 + \frac{\Omega_2}{g_2}\hat{a}_2 , \qquad (1)$$

where g_i is the vacuum Rabi frequency for the *i*th signal mode.

The protocol functions as follows. With only control field 1 initially present, a pulsed optical state in mode 1 is coupled into the medium. While it is propagating, control field 2 is turned on slowly, so the EIT signal mode is adiabatically converted into a superposition (1), which continues to propagate losslessly through the medium [1]. This allows complete transfer of the quantum state of mode $\hat{a}_1$ to mode $\hat{a}_2$, with the temporal shape and intensity of the two control pulses determining the outcome of the process. This protocol resembles STIRAP but is applied to optical rather than atomic states. We have performed a proof-of-principle experiment [2] using the Rubidium D1 line, where both the ground ($5S_{1/2}$) and the excited ($5P_{1/2}$) levels are split into hyperfine sublevels.

2. Slow photon as a charged quasi-particle

The evolution of the spatial characteristics of the EIT signal field is governed by the paraxial approximation, which is equivalent to the Schrödinger equation of a free particle in space. In a multi-Λ system, in the presence of several control fields, the signal field is subjected to a unitary transformation (1), which, in analogy to gauge transformations, modifies the paraxial equation, bringing it to the form

$$i\partial_z \hat{b} = \left[\frac{1}{2k}[-i\nabla_\perp - \vec{A}(x,y)]^2 + V(x,y)\right]\hat{b} , \qquad (2)$$

where k is the wavenumber and the propagation is along the z axis. Eq. (2) is analogous to that of a charged Schrödinger particle in an electromagnetic field described by the quasi-vector potential $\vec{A}$ and a quasi-scalar potential V, which are related to the amplitudes and phases of the two pump fields. By choosing specific spatially inhomogeneous control fields, one can steer the EIT photon inside the cell. We have found specific arrangements of two pump fields which generate quasi-gauge potentials corresponding to (i) a constant electric field, (ii) to a constant magnetic field and (iii) the Aharonov-Bohm effect [3].

3. Quantum tomography of slow light

EIT holds promise as a tool for the storage of quantum information carried by light. We present our experimental progress towards storage of the squeezed state of light. Using an optical parametric amplifier, we produce up to 3 dB squeezed vacuum in a narrowband optical mode resonant with the 795 nm rubidium D1 line. We then convert the squeezed mode to a pulsed form, send it through an EIT cell at an ultraslow group velocity, and subject it to time-domain homodyne tomography to investigate the effect that EIT had on squeezing.

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