

## Resonance Beating of Light Stored Using Atomic Spinor Polaritons

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We investigate the storage of light in atomic rubidium vapor using a multilevel-tripod scheme. In the system, two collective dark polariton modes exist, forming an effective spinor quasiparticle. Storage of light is performed by dynamically reducing the optical group velocity to zero. After releasing the stored pulse, a beating of the two reaccelerated optical modes is monitored. The observed beating signal oscillates at an atomic transition frequency, opening the way to novel quantum limited measurements of atomic resonance frequencies and quantum switches.

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Electromagnetically induced transparency (EIT) is a quantum interference effect that allows for the transmission of light through an otherwise opaque atomic medium [1]. More specifically, an optical “control” beam is used to dress the medium to allow for the transmission of optical pulses from an optical “signal” beam. Media exhibiting EIT have remarkable properties, as very low group velocities [2–4]. Associated with a slow light propagation are quasiparticles, the so-called dark polaritons, which propagate through the medium with the speed of the group velocity. The group velocity can even be reduced to zero in a controlled and reversible way, which allows for the storage of light. Notably, also nonclassical states of light, as single-photon or squeezed states, have been stored and retrieved in atomic ensembles in a series of impressive experiments [5–7]. Applications in quantum information science have been suggested [8]. However, a quantum bit  $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$  has two basis states, so that qubits cannot be stored in a single atomic interaction region when using conventional EIT media consisting of atoms with a  $\Lambda$ -type coupling scheme, which exhibit a single dark state. In a recent remarkable experiment, photonic quantum bits have been stored in a superposition of two spatially separated EIT interaction regions [9]. It is however clear that such a spatial separation makes the system sensitive to (inhomogeneous) magnetic stray fields and optical path length fluctuations. Thus multicomponent dark polaritons are of interest, as these should allow for the storage of photonic qubits in a single atomic ensemble.

Our work builds upon an ensemble of atoms in a tripod-type level configuration, where an internal state subspace immune to spontaneous decay spanned up by two orthogonal dark eigenstates exists [10,11]. It has been suggested that onto this two-dimensional decoherence-free subspace qubits can be encoded, and the system should allow for interesting quantum manipulation [12] and geometric phases [13]. Other theoretical work has shown that in an ensemble of atoms with tripod level structure (“tripod medium”) two optical modes with slow group velocity can exist [14].

Here we demonstrate the reversible storage of amplitude and relative phase information of two optical fields in rubidium atomic vapor. Effectively, slow light spinor states are stored and coherently retrieved from the atomic ensemble. It is suggested that the coherent propagation of light through the tripod medium can be described by a dark polariton with an internal two-level structure, whose group velocity can be dynamically varied to zero, thereby mapping photonic qubits onto an appropriate spin coherence information. We furthermore show that after the storage procedure, the observed beat frequency of the two reaccelerated optical fields is determined by the energetic splitting between two ground state sublevels. The difference frequency of the emitted beams remains synchronized to an atomic resonance frequency, so that the operation of our experiment can be characterized as a stored light atomic clock.

Before proceeding, we point out that the two-dimensional dark subspace of the tripod medium has an equal number of degrees of freedom as a free photon of given frequency in the quantum state  $|\psi\rangle = \alpha|H\rangle + \beta|V\rangle$ , where  $|H\rangle$  and  $|V\rangle$  denote two polarization eigenstates. Correspondingly, tripod media can be used to slow down (and store) photons of arbitrary polarization.

For a simple model of dark state polaritons in a tripod medium, consider the level scheme of Fig. 1 with three stable ground states  $|g_-\rangle$ ,  $|g_0\rangle$  and  $|g_+\rangle$  and one spontaneously decaying excited state  $|e\rangle$ . An ensemble of such four-level atoms is resonantly coupled to a strong, classical control laser field connecting states  $|g_0\rangle$  and  $|e\rangle$  with Rabi frequency  $\Omega_C$  and two weak, quantum signal fields described by field operators  $\hat{E}_1(z, t)$  and  $\hat{E}_2(z, t)$  connecting the quantum states  $|g_-\rangle$ ,  $|e\rangle$  and  $|g_+\rangle$ ,  $|e\rangle$ , respectively, where we assume equal atom-field coupling constants  $g$  for both transitions.

In the absence of a signal field, the combined atom-light system is optically pumped into a state described shortly by  $\hat{\rho}_{\text{vac}} = \frac{1}{2}(|g_-\dots g_-\rangle\langle g_-\dots g_-| + |g_+\dots g_+\rangle\langle g_+\dots g_+|)|0\rangle_1|0\rangle_2\langle 0|_1\langle 0|_2$  determined by an incoherent superposition of half the atoms in state  $|g_-\rangle$

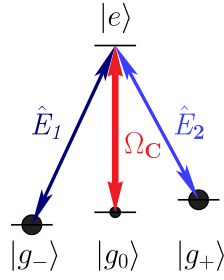


FIG. 1 (color online). Simplified scheme of relevant levels, as used for the theoretical calculations described in the text. The levels  $|g_0\rangle$  and  $|e\rangle$  are coupled by one strong control field with the Rabi frequency  $\Omega_C$  while the two signal fields described by the quantum field operators  $\hat{E}_1$  and  $\hat{E}_2$  drive transitions between  $|g_-\rangle$  and  $|e\rangle$  and  $|g_+\rangle$  and  $|e\rangle$ , respectively. The dots are to indicate the ground state populations.

and half in state  $|g_+\rangle$ , while both signal fields are in the vacuum state. The state described by this density matrix is named the polariton vacuum state (in analogy to the work reported in [15]). Petrosyan and Malakyan showed that in such a medium with  $N$  uniformly distributed atoms per unit length two dark signal fields propagate, both with group velocity  $v_g = c/(1 + \frac{Ng^2}{2\Omega_C^2})$  [14]. Starting from the solutions found by Fleischhauer and Lukin for a three-level medium [15], we can due to the linearity of the Hamiltonian for small signal field strengths construct the corresponding dark polariton states for the tripod medium:

$$\hat{\Psi}_{\pm}(z, t) = \cos\Theta \hat{E}_{1,2}(z, t) - \sin\Theta \sqrt{N/2} \hat{\sigma}_{\pm,0}(z, t), \quad (1)$$

where  $\tan\Theta = \sqrt{N/2}g/\Omega_C$  and  $\hat{\sigma}_{\pm,0} = \frac{2}{N} \sum_{j=1}^N |g_{\mp}\rangle \langle g_0|$  are spin-flip operators. Further, we can define

$$\hat{\Psi}(z, t) = \alpha \hat{\Psi}_+(z, t) + \beta \hat{\Psi}_-(z, t), \quad (2)$$

as the two-state polariton operator. The group velocity  $v_g = c \cos^2\Theta$  can dynamically be varied, so that we expect that such “spinor polariton states” can be coherently mani-

pulated analogous to usual slow and stored light experiments.

A one-polariton state can be generated using this operator, which yields  $\hat{\Psi}^\dagger \hat{\rho}_{\text{vac}} \hat{\Psi}$ . It is interesting that the operators  $\hat{\Psi}_{\pm}$  (as well as the qubit state  $\hat{\Psi} = \alpha \hat{\Psi}_+ + \beta \hat{\Psi}_-$ ) describe pure polariton states, though they act on an incoherent ensemble. Using these polariton operators repeatedly, we can also construct different polariton Fock states [15] or coherent polariton states [16], which are expected to be closest to the actual states produced in our experiment that is carried out with classical optical fields.

Our experimental setup is similar as described previously [17,18], and a schematic is shown in Fig. 2(a). A 50 mm long rubidium vapor cell filled with 10 torr of neon buffer gas placed into a magnetically shielded region is heated to approximately 100 °C. Both optical signal fields and the control field are derived from the same grating stabilized diode laser, locked to the  $F = 2 \rightarrow F' = 1$  component of the rubidium  $D1$ -line near 795 nm. Its emitted radiation is split into two beams, both of which pass an acousto-optic modulator. One of the paths is used to generate the optical signal fields and the corresponding modulator is driven with two distinct radio frequencies to generate the two signal beam frequencies  $\omega_{S1}$  and  $\omega_{S2}$ . The other modulator is driven with a single radio frequency to produce the optical frequency of the control field. The beam paths are overlapped, sent through an optical fiber, and before entering the rubidium apparatus expanded to a 2 mm beam diameter.

A full level scheme of our rubidium system is shown in Fig. 2(b). The  $F = 2$  ground state has 5 Zeeman components, while the  $F' = 1$  excited state has 3 sublevels. As in the simplified scheme of Fig. 1 the conclusion remains valid that two dark states exist, as the characteristics of a tripod medium. The rubidium cell is subject to a 150 mG homogeneous magnetic bias field directed transversely to the propagation axis of the optical beams. The control beam has  $\pi$ -polarization, so that in the absence of signal beam light the atoms will be pumped into an incoherent superposition of the two Zeeman ground states  $m_F = -2$

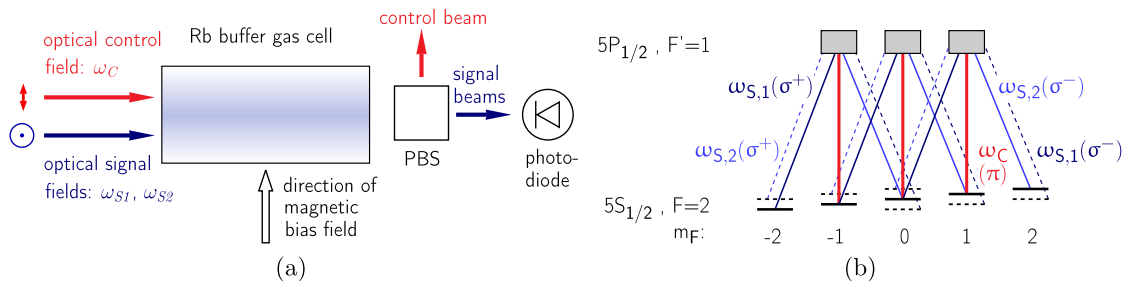


FIG. 2 (color online). (a) Scheme of the experimental setup. The input quantum state, encoded in a superposition of the two signal fields with optical frequencies  $\omega_{S1}$  and  $\omega_{S2}$ , is reversibly stored in a rubidium buffer gas sample. The optical control field with frequency  $\omega_C$  has an orthogonal linear polarization with respect to the signal fields. The signal fields and the control field are spatially overlapped upon entry into the rubidium cell. (b) Full scheme of the rubidium levels addressed by the two signal fields and one control field (solid lines). Also shown are the off-resonant circularly polarized components of the signal beams, i.e., the component with frequency  $\omega_{S2}$  and  $\sigma_+$ -polarization and that with frequency  $\omega_{S1}$  and  $\sigma_-$ -polarization (thin dashed lines).

and  $m_F = 2$  respectively. Both signal fields have the same  $\sigma_+ \sigma_-$  (i.e., linear) polarization. Signal field 1 (2) is tuned to a frequency  $\omega_{S1} = \omega_C + \frac{\mu_B B}{2}$  ( $\omega_{S2} = \omega_C - \frac{\mu_B B}{2}$ ), where  $\omega_C$  denotes the optical frequency of the control field. Thus, the  $\sigma_+$ -component of signal field 1 along with the  $\sigma_-$ -component of signal field 2 and the  $\pi$ -polarized control field give the usual coupling scheme of a tripod system. Note that the  $\sigma_-$ -polarized component of field 1, and the  $\sigma_+$ -polarized component of field 2 [indicated as dashed lines in Fig. 2(b)] provide decay channels, so that we expect the dark states to show a nonzero leakage; i.e., strictly speaking we have gray states [19]. After passing the rubidium cell, control and signal beams are separated with a polarizing beam splitter and the total intensity of both signal fields is detected on a photodiode.

In initial experiments, we have monitored the preparation of dark states in our experimental configuration using cw signal and control fields. Figure 3(a) shows (averaged) optical transmission spectra of the total signal field as a function of the signal beam frequencies, both of which were independently tuned. The signal beam power is  $130 \mu\text{W}$  per beam and the control beam power is  $270 \mu\text{W}$ . We observe an increased transmission when either the two-photon detuning  $\delta_1 = \omega_C - \omega_{S1} + \frac{\mu_B B}{2}$  or  $\delta_2 = \omega_C - \omega_{S2} - \frac{\mu_B B}{2}$  approaches zero, in which case  $\sigma_+ - \pi$  ( $\sigma_- - \pi$ ) polarized optical fields probe whether there is destructive interference of excitation amplitudes. As expected, the overall transmission signal is maximized near  $\delta_1 = \delta_2 = 0$ , the region of tripod-type transparency with two dark states. We wish to point out that tripod-type

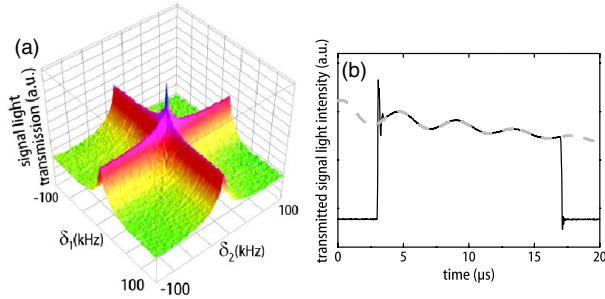


FIG. 3 (color online). (a) Total signal beams transmission signal (dc photodiode signal) averaged over 10 scans versus the two-photon detunings  $\delta_1$  and  $\delta_2$ . A visible small modulation near the line determined by  $\delta_1 + \delta_2 = 0$  is instrumental and attributed to higher order mixing of the signal beams with residual control beam light leaking through our polarizing beam splitter, which near this line of degeneracy also contributes to a signal near dc frequency. (b) Selected part of the photodiode signal after a light storage time of  $10 \mu\text{s}$  (solid curve) fitted with a sinusoidal curve (dashed line). This modulation arises from the beating between two reaccelerated optical modes and is interpreted as evidence for their relative coherence. The rectangular shape of the pulse form is determined by the gated signal processing of the electronic signal, and the visible spiking at the beginning is attributed to transients of this electronics.

dark resonance physics has also been investigated in [10,11,20]. In other preparatory experiments, we observed slow light by pulsing the signal beams. Typical observed group velocities were  $1700 \text{ m/s}$  with the tripod system.

We then moved to a storage of light in the tripod polarization system. The input signal pulses typically used were rectangularly shaped and had a temporal length of  $20 \mu\text{s}$ . The intensity of the control beam is ramped to zero at the falling edge of the signal beams pulse. After a storage time of typically  $10 \mu\text{s}$ , only the control beam was pulsed on. Figure 3(b) gives a typical result obtained when storing a pulse performed with both signal fields simultaneously. The plot shows the obtained photodiode signal, onto which both signal beams are imaged behind the cell, after gated signal processing. We observe a slow decay in the retrieved signal beams pulse, on which a sinusoidal modulation is visible. We attribute this modulation to the beating of the two retrieved signal beams fields. From this result we conclude that simultaneous storage of two signal fields is possible and that their relative phase information is preserved. Note that here, the photodiode signal was electronically shut off by a switch during the storage period and processed in the part of the readout period where the amplitude of the beat signal was sufficiently large. Because of this detection technique the depicted shape of the readout pulse is rectangular rather than exponentially decaying to zero.

Using the tripod scheme, we can exploit the full two-dimensional subspace that is dark for the light field in this configuration. Qualitatively, the experiment can be understood by considering the simplified level scheme of Fig. 1. By shutting off both signal beams and the control beam adiabatically, the state of the propagating input light field is mapped into a spin-wave coherence in the tripod system with 2 degrees of freedom. When the signal beam pulses are contained within the medium, the coherence of the laser fields is already imprinted on the atoms. As the control laser is turned back on, the signal laser pulses are regenerated by adiabatic following mapping atomic coherences again into the corresponding signal field modes. The

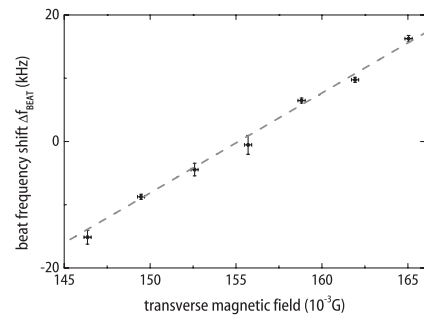


FIG. 4. Measured beat frequency shift of the released signal beams, after storage as a function of the applied (transverse) magnetic field. For all shown data points, the atomic sample was irradiated with optical signal fields of the same frequency during the storage procedure.

pulses continue to propagate under tripod-EIT conditions as prior to the turn-off of the control beam. The interference observed between the two released signal fields shows their relative coherence, which we interpret as the beating of two polariton modes. Note that in contrast to the free photon case, where the spin direction is parallel to the propagation direction, in our experimental configuration for each of the polariton modes the atomic contribution of the spin wave state is directed transversely to the propagation direction.

In subsequent experiments, we have varied the magnetic bias field over a region within the spectral width of the EIT resonance. Figure 4 shows the difference between the measured beat frequency and the incident signal beams difference frequency as a function of the magnetic bias field. We observe a linear dependence of the beat frequency on the magnitude of the magnetic field. Within our experimental accuracy, the beat frequency equals the Zeeman splitting  $2g_F\mu_B B$  of a  $\Delta m_F = 2$  Raman coherence in the used rubidium  $F = 2$  ground state system, where  $g_F$  is the (hyperfine)  $g$  factor that equals  $1/2$  here. Note that all shown data points have been recorded with the same signal beams difference frequency. That is to say, while the storage of light can be done with frequency difference somewhat differing from the atomic (Raman) transition frequency, as long as one is within the EIT transparency window, the retrieved optical difference frequency within our experimental accuracy is determined by the atomic transition frequency of the ground states  $|g_-\rangle$  and  $|g_+\rangle$  of the tripod coherence (i.e. the Zeeman states  $m_F$  and  $m_F + 2$  of the rubidium level scheme). This result is expected, since the storage onto a spin-wave coherence imprints phase and amplitude information. Further, the regenerated optical dipole for a  $\sigma_+$  ( $\sigma_-$ ) transition oscillates at a frequency  $\omega_C \pm g_F\mu_B B$ , where  $\omega_C$  denotes the control beam frequency and  $g_F\mu_B B$  the Zeeman splitting between two adjacent magnetic ground state sublevels. The difference frequency between the two retrieved signal beams is thus expected to be  $2g_F\mu_B B$ . The spinor polariton system acts as an atomic frequency converter; i.e., coherences stored in the system at a particular signal beam difference frequency after storage are converted to the atomic (signal beams) transition frequency.

We conjecture that these experiments pave the way towards a storage of quantized signal beams states, where, e.g., squeezed signal light states would be of particular interest. Since the light storage despite its frequency conversion to the atomic transition frequency is expected to conserve the quantum properties, we expect that measurements of the retrieved signal beams difference are possible with sub-shot noise precision, allowing for quantum limited measurements of magnetic fields and atomic transition frequencies. We anticipate that with a suitable mechanism for driving the internal two-level structure of the spinor polariton an all-optical quantum frequency switch can be implemented.

To conclude, we have stored light in an ensemble of tripod-type atoms, demonstrating the mapping of dark polaritons with internal two-level structure into spin-wave coherences and their coherent retrieval. Also, we have shown that the retrieved difference frequency of the emitted signal beams is determined by the atomic transition frequency of ground state Zeeman sublevels.

For the future, we anticipate applications of dark polaritons with internal structure in the fields of quantum limited precision metrology and quantum information.

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