From four-wave mixing to Hamiltonian engineering in readout proccess of Raman memory

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We demonstrate experimentally the theoretical concept of "Hamiltonian engineering" proposed in [1]. We design the Hamiltonian at the readout from Raman atomic memory in warm ^{87}Rb vapors. In such memory photons are stored in atomic collective excitations called spin-waves and interfaced to photons via off-resonant Raman transitions.

We begin by synthesizing a simple, plane-wave theoretical model of the readout by four-wave mixing (FWM) from a Raman memory [2] to qualitatively support our experimental results. In our experiment we induced spontaneous Stokes scattering using write pulse with a wave vector $\mathbf{k}_\mathrm{W}$ to populate the spin-waves, i.e. collective atomic excitations from the levels $|0\rangle$ to $|1\rangle$ as in Fig.1(a). Ideally, the number of created spin-wave excitations n_b ($\hat{b}^\dagger$ - mode) with a certain wave vector $\mathbf{K}_b$ equals the number of scattered Stokes photons ($\hat{a}^\dagger_\mathrm{WS}$ - mode) with wave vector $\mathbf{k}_\mathrm{WS} = \mathbf{k}_\mathrm{W} - \mathbf{K}_b$. We were able to estimate those numbers in each single iteration of the experiment.

Here we focused on the retrieval stage at which the spin-wave excitations are converted to photons in FWM induced by the read laser pulse depicted in Fig.1(b). The read laser is assumed to be plane-wave with a wave vector $\mathbf{k}_R$. Spin-wave with a certain wave vector $\mathbf{K}_b$ are coupled to anti-Stokes and Stokes fields (into modes $\hat{a}^\dagger_\mathrm{RA}$ and $\hat{a}^\dagger_\mathrm{RS}$) with wave vectors $\mathbf{k}_\mathrm{RA} = \mathbf{k}_\mathrm{R} + \mathbf{K}_b$ and $\mathbf{k}_\mathrm{RS} = \mathbf{k}_\mathrm{R} - \mathbf{K}_b$ respectively. In the experiment those weak light fields illuminated distinct pixels of the camera which was located in the far field. They were also shifted with respect to the initial Stokes photons with the wave vector $\mathbf{k}_\mathrm{WS} = \mathbf{k}_\mathrm{W} - \mathbf{K}_b$ due to different direction of the write beam $\mathbf{k}_\mathrm{W}$.

The Hamiltonian describing the Stokes and anti-Stokes scattering in the readout proccess can be written as [3]:

$$\hat{H}_\mathrm{R} = i\hbar\chi\hat{a}^\dagger_\mathrm{RA}\hat{b} + i\hbar\xi\hat{a}^\dagger_\mathrm{RS}\hat{b}^\dagger + H.c.$$

where χ and ξ are the coupling coefficients for anti-Stokes and Stokes Raman transitions. By modifying the interaction Hamiltonian we are able to control the relative contributions of anti-Stokes and Stokes scattering processes. In the particular setting of our experiment changing the detuning of Raman pump laser from atomic resonance enables parametric amplification of the readout, albeit with extra noise.

In the experiment we detect scattered light with spatial resolution and temporal gating using a gated image intensifier coupled to sCMOS camera. This enables directly relating the experimental results to the theoretical predictions for temporal evolution of scattered light. Stokes and anti-Stokes light contributions can be distinguished through intensity correlation measurements (Fig.2) and quantified via careful post-processing [4].

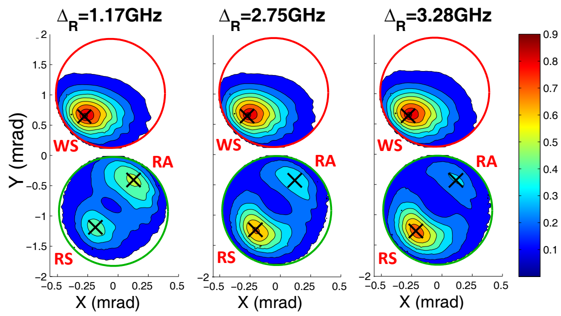

FIG. 2. Correlation maps between Raman scattered light during the write-in (up) and readout (bottom) processes for different readout laser detuning Δ_R from ^{87}Rb F = 2 → F′ = 2 resonance on D1 line. Measurement was done using intensified sCMOS camera.

Our results provide a very simple framework for interpretation of extra noise in experiments on storing light in atomic vapor. When anti-Stokes scattering is used to map the spin-wave states onto the states of light, the accompanying Stokes scattering creates unwanted random photons and atomic excitations. This contribution can be estimated by our model and suppressed by adjusting the coupling light frequency to the other side of the atomic resonance. There is also an optimal duration for the anti-Stokes interaction. Beyond the optimum, the spontaneous noise contribution increases. The amplification in the readout can be utilized as a robust single-shot projective test to see whether the atomic memory is in the ground state.

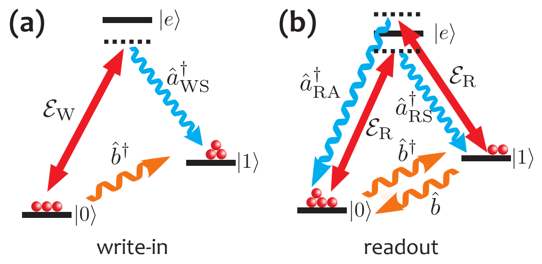

FIG. 1. Atomic levels and phase matching in Λ-scheme Raman scattering induced by classical laser field $\mathcal{E}_\mathrm{W}$ and $\mathcal{E}_\mathrm{R}$ for write-in (a) and readout (b) processes. See text for further details.

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