Tailored State Preparation for Solid-State Quantum Memory*

E.A. Goldschmidt[1,2], S.V. Polyakov[1,2], S.E. Beavan[1,3], J. Fan[1,2], and A.L. Migdall[1,2]
[1]*Optical Technology Division, National Institute Standards and Technology, 100 Bureau Drive, Gaithersburg, Maryland 20899, USA*
[2]*Joint Quantum Institute, University of Maryland, College Park, Maryland 20742, USA*
[3]*Laser Physics Centre, RSPhysSE, Australian National University, Canberra, ACT 0200, Australia*
elizabeth.goldschmidt@nist.gov

Abstract: We report progress in implementing a quantum memory scheme in Pr^{3+}:Y_2SiO_5, including experimental and theoretical results using spectral hole-burning to generate narrow absorbing features and implement narrow spectral filtering.

OCIS codes: (270.5585) Quantum information and processing; (160.5690) Rare-earth-doped materials

Quantum communication has spawned much interest in recent years, however long-distance quantum communication requires quantum memory that can locally store qubits in matter-based internal states and use shared entanglement to overcome the exponential loss of photonic channels. Rare earth ion-doped crystals are promising candidates for ensemble-based quantum memory because they are solid-state systems with narrow optical transitions and seconds-scale coherence times [1]. We use one such material, Pr^{3+}:Y_2SiO_5, to generate single photons and implement the quantum memory protocol of Duan et al. (DLCZ protocol) [2].

One challenge associated with rare earth ion-doped crystals is the large inhomogeneous broadening of the optical transition. The inhomogeneous linewidth of the optical transition (≈10 GHz) is much larger than the splittings between the metastable ground states (Fig. 1(a)). The DLCZ protocol involves scattering a single photon on a specific transition, so state preparation is needed to generate a narrow ensemble of ions. We use spectral hole-burning techniques to create a narrow absorbing feature made up of ions in a particular ground state, on a background emptied of absorbers, and ensure that no ions elsewhere in the spectral profile are resonant with the optical transitions of our selected ions. We use a three-step hole-burning scheme like that described by Nilsson et al. (Fig. 1(b)) [3]. We experimentally implement this procedure and observe the resulting spectral profile by measuring absorption of a weak probe field scanned in frequency across the holes made by the $P_{1/2}$ and $P_{3/2}$ fields (these holes merge into one due to the range that the fields are scanned, see fig. 1(c)). We see a tall, ≈1 MHz wide peak due to absorption on the $\pm 3/2 \rightarrow \pm 1/2$ transition of our selected frequency class on a background emptied of absorbers. We also see small peaks due to a small amount of population pumped back into the $\pm 1/2$ ground state in step three.

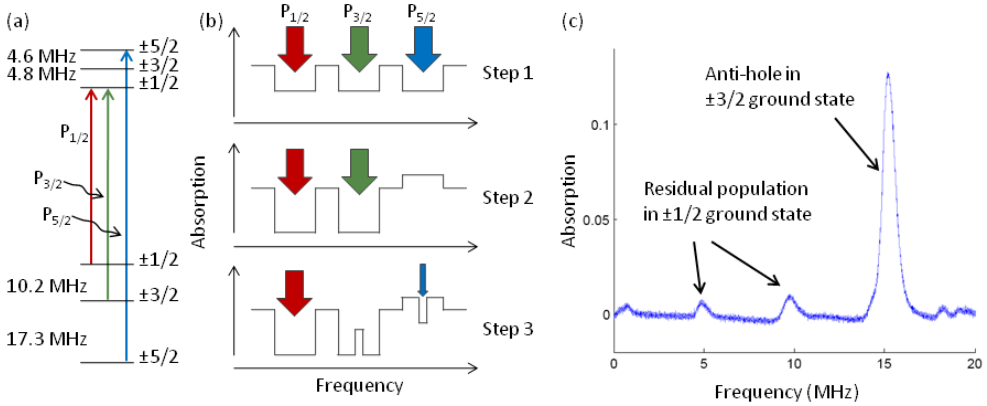

Fig. 1. (a) Energy level structure and hole-burning fields. (b) Schematic of hole-burning sequence. Step 1 pumps ions in undesired frequency classes to non-resonant states, step 2 pumps all ions in the selected frequency class into a single ground state, step 3 creates a narrow absorbing feature in one of the empty ground states. (c) Absorption of a weak probe field vs. frequency following experimental realization of the hole-burning sequence.

We have modeled the spectral hole-burning process in our system and optimized the parameters for step one of the state preparation scheme. We model spectral hole-burning as an incoherent process, using standard population rate equations, and find both time-evolved and steady-state solutions. To optimize the process we want to minimize the population in undesired frequency classes that is resonant with any of the three hole-burning fields. Thus, the figure of merit, which we minimize, is this unwanted population, weighted by transition strength, and normalized to an initial flat population distribution (Fig. 2).

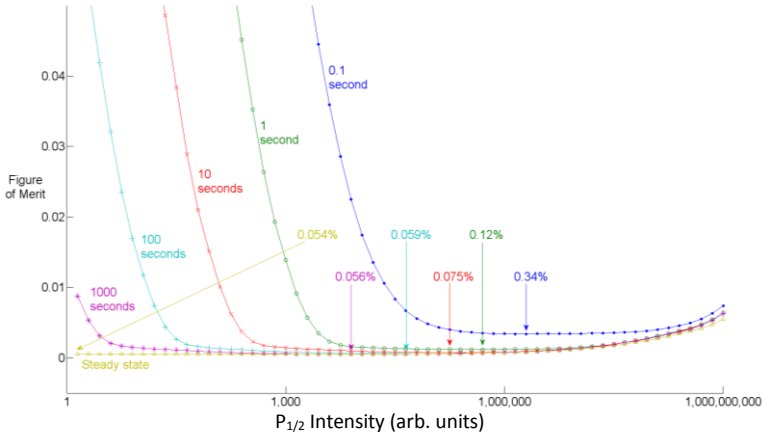

Fig. 2. Figure of merit (which we minimize) vs. intensity in one hole-burning field. Shown are time evolved solutions for five total sequence times (noted) and the steady-state solution. Intensities in the other two fields are optimized at each point. Minima are noted for each curve.

We find that the steady-state solution in the limit of zero field intensity provides a lower limit the figure of merit and that we can achieve a figure of merit within an order of magnitude of this limit for even relatively short sequence times.

We also use spectral hole burning to implement a narrow spectral filter in order to separate the fields we use to optically access the qubit states (±1/2 and ±3/2 ground states), which are split by 10.2 MHz. This requires a ≈3 MHz wide hole, for efficient transmission, with strong absorption 10.2 MHz away. However, a single hole-burning does not create a single narrow hole. The multi-level energy structure of the material (Fig. 1(a)) leads to many side holes and laser drift on a time scale slower than the experiment, but faster than the hole refill time, causes deformation of the hole. Thus, in addition to the main hole-burning field we employ cleanup pulses far away from the hole (≈22 MHz) to refill the space at ±10.2 MHz and ensure strong absorption. After applying these hole-burning fields we send weak pulses of light through this filter at a small angle. Fig. 3 shows the transmission of these pulses for the filter centered on the pulse wavelength and detuned by ±10.2 MHz. We see up to 20 dB attenuation of the off-resonant pulses.

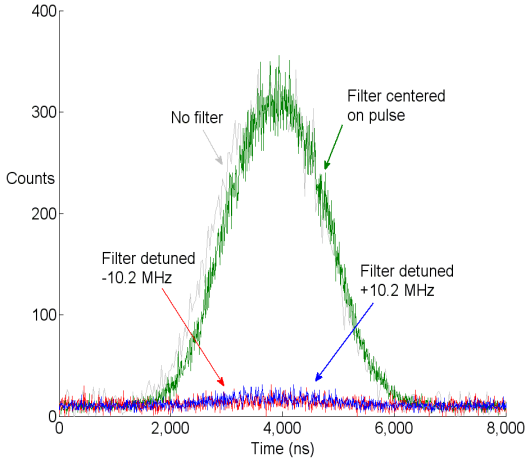

Fig. 3. Time-binned photon counts of short pulses with filter tuned to the wavelength of the light (green) and detuned by ±10.2 MHz (blue/red). An unfiltered reference pulse (gray) shows that the filter does not significantly alter the temporal shape of the transmitted field. The slight delay of the filtered pulse compared to the unfiltered pulse can be attributed to the group velocity delay from the opening of a narrow transparency window.

We have described experimental and theoretical progress toward implementing a DLCZ-type quantum memory scheme in Pr^{3+}:Y_2SiO_5. In particular, we have described our use of spectral hole-burning techniques to prepare an ensemble of ions with the appropriate spectral distribution for our quantum memory proposal and to implement narrow spectral filtering.

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