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Single-photon level quantum memory in an isotopically pure ^{143}Nd^{3+}:Y^{7}LiF$_4$ crystal

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1. Introduction. Quantum memory [1] is a key element for developing modern quantum technologies and most importantly long range quantum communication [2]. One of the more promising media for implementing quantum memory protocols are inorganic crystals doped with rare earth ions [3, 4]. They have several key advantages, including, most notably, their long coherence times [5]. There are different approaches to implementing quantum memory in such media, using, for example, electromagnetically induced transparency [6, 7], controlled and reversible inhomogeneous broadening (CRIB) [8, 9] or revival of silent echo (ROSE) [10, 11].

In the present paper we choose the atomic frequency comb (AFC) protocol [12] for implementing our quantum memory. This protocol relies on creating a periodic structure within the inhomogeneously broadened optical transition. When a pulse with a spectral width slightly lower than the structure width is sent into the media, it is absorbed (stored) [13] and reemitted (recalled) after a time inversely proportional to the structure period. There are variations of the protocol capable of increasing the storage time and performing on demand readout [12]. The AFC protocol offers high efficiency, large multimode capacity [14] and a relative ease of experimental implementation.

In order to realize the quantum memory we use an isotopically pure Y^{7}LiF$_4$ crystal (containing 99.7 % of ^{7}Li) doped with Nd ions (containing 96.5 % of ^{143}Nd^{3+}) that is cooled down to cryogenic temperatures. Nd ions in this crystal have a relatively strong working transition with the wavelength of around 867 nm lying in the optical fiber transparency window. Optical transitions in isotopically pure host crystals have small inhomogeneous broadening (around 100 MHz for our crystal) and such crystals also demonstrate longer population relaxation and spin coherence times.

Previously we studied the properties of quantum memory in this media using classical bright pulses [15, 16]. The present work is dedicated to implementing a quantum memory at the single photon level. Going down to single photon level is essential for various applications in quantum information science that involve storage of entanglement, e.g. quantum repeaters [17, 18].

2. Experiment. We use the following experimental setup. A 5 mm long ^{143}Nd^{3+}:Y^{7}LiF$_4$ crystal with the Nd dopant concentration of 0.005 at. %, cut along the c crystallographic axis, is placed into an optical cryostat cooling the sample down to around 4 K. A single frequency Ti : Sapphire laser is used to address one of the hyperfine components of the Nd ion ^{4}I$_{9/2}(1) \rightarrow {}^4F_{3/2}(1)$ transition (~ 867 nm wavelength). The crystal is placed so that the c axis is along the light propagation direction. In order to implement the comb burning sequence we use an acousto optical modulator.

One of the difficulties on the path towards implementing quantum memory at the single photon level is noise. The main source of noise is the fluorescence of the ion population on the upper levels that is excited during the comb burning sequence. The fluorescence decays with time, so one of the ways to reduce this noise is to introduce a delay between the creation of the AFC and sending the storage pulses [19]. The downside of this approach is that the comb degrades due to the ground state population relaxation and the memory efficiency decreases with time.

We measure this fluorescence and find that under our experimental conditions within 5 ms it decays to acceptable ~ 65 counts per second (2.5 times higher than the dark count rate). We also measure the dependence of the memory efficiency on the delay after the burning sequence. These measurements are performed in the "bright" pulse regime and they show that in 5 ms (we choose this delay for the further single photon level experiments) the efficiency decreases twofold from the initial value of around 13 %.

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In order to observe the memory at the single photon level we use a combination of an optical chopper and a shutter to protect the single photon detectors during the comb burning sequence. Afterwards these shutters are opened and we send a set of 100 short (duration of 20 ns) pulses separated by 10 μs into the memory. Each pulse is weakened by filters so that it contains ~ 0.98 photons on average. At the delay of ~60 ns after the input pulse (corresponding to the 16 MHz comb period) we observe the echo signal (see Fig. 1). The efficiency at the single photon level is around 6.4 % which is comparable to the results observed with the classical "bright" pulses. The signal to noise ratio in our experiment is around 3 and mostly limited by the leftover fluorescence from the comb burning sequence.

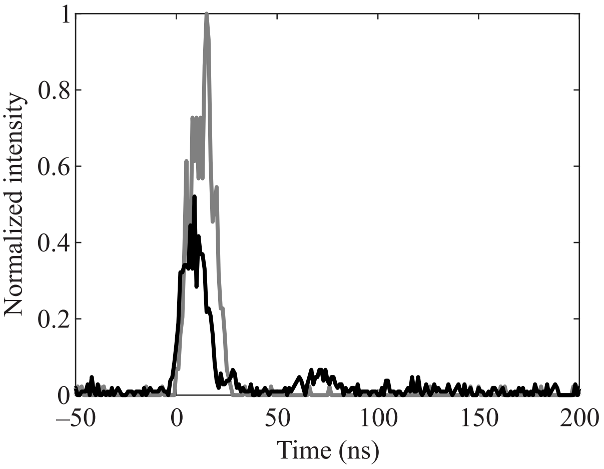

Fig. 1. Echo signal – black line. The grey line shows the input pulse

3. Conclusion. In an isotopically pure $^{143}\mathrm{Nd}^{3+}{:}\mathrm{Y}^{7}\mathrm{LiF}_4$ crystal we demonstrate the possibility of creating a single photon level quantum memory based on the atomic frequency comb protocol. We perform storage and readout of the weakened laser pulses with the average photon number of around 1. The resulting efficiency of 6.4 % is comparable to the memory efficiency for the "bright" pulses.

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Conflict of interest. The authors of this work declare that they have no conflicts of interest.

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