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Solid-state Raman quantum memory in whispering gallery mode resonators: signal-to-noise ratio

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Abstract. The possibility of implementation of optical quantum memory via off-resonant Raman absorption and emission of single-photon pulses in rare-earth-ion-doped crystals is theoretically analysed taking into account signal-to-noise ratio at the output of the memory device. The crystal $^{143}Nd^{3+}:Y^{7}LiF_4$ is considered as an example. It is shown that the signal-to-noise ratio can exceed unity for single-photon input pulses provided that storage and retrieval of them is performed in the doped crystals forming a microcavity such as whispering gallery mode resonator.

1 Introduction

Quantum memories are of crucial importance for developing quantum information technologies and form a platform for building scalable linear optical quantum computers, realizing long-distance quantum communications, etc. (see [1, 2] for a recent review). One of the most commonly discussed materials are rare-earth-ion-doped solids [3], in which the phase relaxation time at cryogenic temperatures may be as long as several hours [4]. Among them, isotopically pure crystals are of particular interest. They can demonstrate very small inhomogeneous broadening of optical transitions, reaching tens of MHz, which proves to be smaller than the hyperfine splitting of the energy levels of impurity ions. As a result, these crystals are promising candidates for implementing memory protocols based on off-resonant Raman interaction [5-7]. In the present work, we analyse the possibility of implementing optical quantum memory via off-resonant Raman absorption and emission of single-photon pulses in such crystals placed in a cavity and achieving large signal-to-noise ratio at the output of the memory device.

2 Basic results

To consider cavity-assisted quantum memory, we take the advantage of a theoretical model developed in [8]. The model is applied for analysis of the signal-to-noise ratio which

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can be obtained in the isotopically purified crystal $^{143}Nd^{3+}$:Y^7LiF_4, which has been used recently in experiments [9, 10] for implementing atomic-frequency-comb-based protocols of quantum memory. It is shown that the signal-to-noise ratio can exceed unity for single-photon input pulses provided that storage and retrieval of them is performed in the doped crystals forming a whispering gallery mode (WGM) resonator.

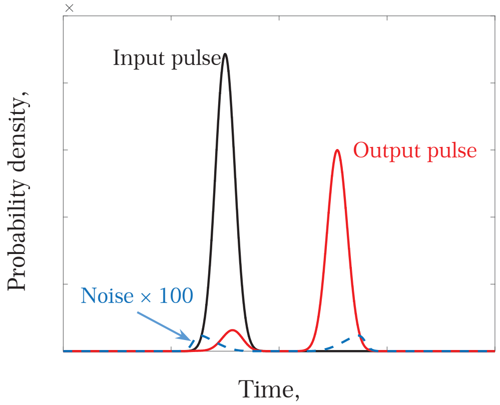

Fig. 1. Illustrating storage and retrieval of single-photon Gaussian pulses in $^{143}Nd^{3+}$:Y^7LiF_4 crystal.

To be more precise, we consider a WGM resonator of 200 μm in diameter with Q-factor of ~ 10^8. The latter corresponds to the cavity finesse of ~ 10^5, which is a typical value for such a type of resonators. In addition, we consider an ideal Λ-scheme corresponding to ZEFOZ spin transition that can be formed in this crystal under application of a weak magnetic field [8]. Then, according the numerical simulation, we can obtain less than 1% of noise at the output of the memory, which strongly depends on the number of impurity atoms. In particular, taking the dipole moment of the optical transitions 0.003 D and the maximum value of the control field Rabi frequency 8.4 MHz, we obtain 0.5% (0.08%) of noise for $1.4\cdot10^5$ ($7\cdot10^4$) ions. Fig. 1 displays the result of the simulation for Gaussian pulses of 425 ns duration.

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