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Rabi Oscillation in $^{167}Er^{3+}$ toward quantum memories

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Quantum storage devices such as quantum memories are necessary for quantum information processing. The purpose of the quantum memory is to store photons faithfully and output them on demand. Rare earth doped crystals have been subjected to extensive research on the quantum memory due to long radiative lifetime and coherence time. Erbium ion (Er^{3+}) is one of the most desired ions because of its optical transition wavelength of 1.53 µm, which corresponds to wavelengths used in telecom band. To use Er^{3+} as a quantum memory, one must coherently control optical transitions by applying light source. Here, we demonstrate the control of optical transitions ($^4I_{15/2}$ – $^4I_{13/2}$) by showing optical Rabi oscillation in isotopically purified $^{167}Er^{3+}$:Y_2SiO_5 bulk crystals. The observation of Rabi oscillation means that we are able to coherently control optical transition and this result opens up possibilities for quantum memory at telecom wavelength.

1. Introduction

Quantum memory can become a desired candidate for realizing quantum network as a node [1]. It is expected to store photons for a long time and release them whenever we want. Rare earth doped crystals are promising candidates for the quantum memories because of their favorable optical properties, among which the most important are long radiative lifetime T_1 and coherence time T_2, approaching $T_2 = 2T_1$. [2] In particular, erbium ions (Er^{3+}) have an optical transition at ~ 1.53 µm which corresponds to the telecom band wavelength. Recent researches reported Er^{3+} ions doped crystals employing protocols for storing photons, such as atomic frequency combs (AFC) [3] and gradient echo memory (GEM) [4]. They contributed to realizing telecom-band quantum communication network but a lot of challenges such as storage time and efficiency still remain. To make use of Er^{3+} as a telecom-band quantum memory, achieving longer storage time and higher efficiency are critical issues. As a way of improving the storage time, using optical transitions in hyperfine levels can be considered. Baldit et al. suggested Λ-like systems in hyperfine levels in $^{167}Er^{3+}$:Y_2SiO_5 for the quantum memory applications (shown in Fig. 1) [5]. We have studied optical properties, radiative lifetime and coherence time of such hyperfine levels [6-8]. In addition to these parameters, Rabi frequency is essential parameter for the coherent control in the Λ-like system because it allows electron population transfer with high efficiency. One of the methods to estimate Rabi frequency is observation of Rabi oscillation, a phenomenon where electron population excited with an external light source, shuttles between two levels periodically and coherently at a resonant frequency. Observing Rabi oscillation requires coherent control of electron transition. Therefore, the achievement of obserivng Rabi oscillation can contribute to realization for quantum storage divices with long storing time and high effficiency. In this study, we demonstrate Rabi oscillation at telecom-band wavelength in isotopically purified $^{167}Er^{3+}$:Y_2SiO_5 crystals.

2. Rabi oscillation scheme

In our experiments, we used isotopically purified $^{167}Er^{3+}$:Y_2SiO_5 bulk crystals as a sample. The concentration of $^{167}Er^{3+}$ was 0.001 %, which is equivalent to 10 parts per million (ppm). The sample in a cryostat was cooled under 2.5 K. The optical frequency of pump pulses was tuned to 195.115828 THz, corresponding to 1536.48456 nm. This frequency matches the transition frequency between hyperfine sublevels shown by the red arrow in the inset of Fig. 2(a). The linewidth of the pulse was 1 kHz. Our method adopted for observing Rabi oscillations was changing pump duration Δt while light power density of pump pulse was kept constant. The definition of Rabi frequency is expressed as $\Omega_R = |\mu E_0 / \hbar|$, where μ is the transition dipole moment and E_0 is the electric field amplitude of the pump pulse. There is a relation between E_0 and light power density $\rho = \frac{1}{2} c \epsilon_0 n E_0^2$, where c is the speed of light in vacuum, ϵ_0 is the dielectric constant of vacuum and n is the refractive index of a vacuum. As the relation shows, maintaining light power density means keeping the electric field amplitude of pump pulse. Therefore, we were able to observe the Rabi oscillations while keeping the Rabi frequency constant.

3. Results and Discussions

Figure 2 shows the measured Rabi oscillations. We can see sinusoidal oscillation of integrated photoluminescence intensity against pump duration Δt. The difference between these two Rabi oscillations is an optical pump power density ρ. Rabi frequency Ω_R depends on ρ, thus each Rabi oscillation has different Ω_R. From the fitting curve, that is damped sine wave, we got about three Rabi cycles in each oscillation. Each estimated Ω_R in Fig. 2 was $2\pi \times 1.9$ MHz and $2\pi \times 0.8$ MHz respectively. From the definition of Rabi frequency, the estimated transition dipole moments were able to be calculated and they were 8.0×10^{-32} Cm and 7.6×10^{-32} Cm. Figure 3 shows the color plot of the dipole moment in the relation between Rabi frequency and power density. This

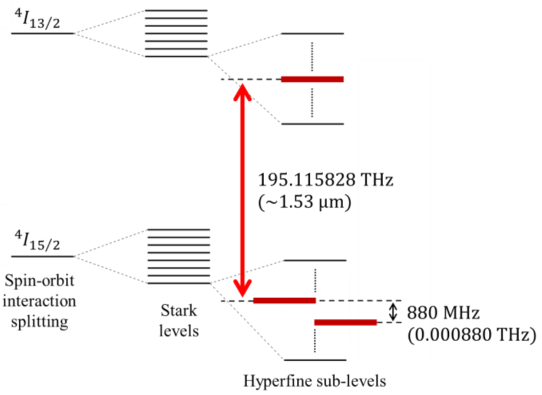

Figure 1. Energy level diagram of $^{167}Er^{3+}:Y_2SiO_5$. The Λ-like system displayed with red was used for our measurement

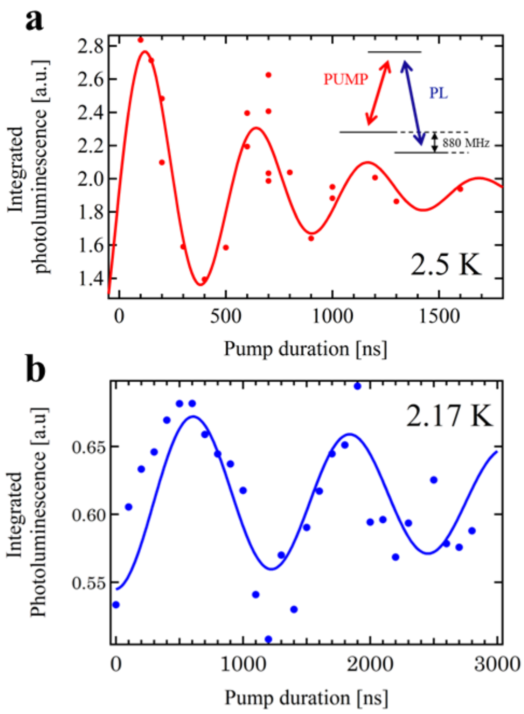

Figure 2. Rabi oscillation between hyperfine levels in $^{167}Er^{3+}:Y_2SiO_5$ using fixed pump intensity while changing pump duration. "**a**" was set at higher optical pump power density ρ than "**b**". The inset shows Λ-like system which we used.

gives us required power density ρ to get arbitrary Rabi frequency. This consistency proves that we measure the genuine Rabi oscillations. We succeeded to observe not only Rabi oscillation but also power dependence of Rabi frequency, which means that we are able to coherently control the optical transitions in Λ-like system in the $^{167}Er^{3+}:Y_2SiO_5$. Therefore, these results open up possibilities for the application of many kinds of protocols because they must be realized during coherence time. As an example of possible protocols, stimulated Raman adiabatic passage (STIRAP) is desirable. STIRAP can transfer electron transition between

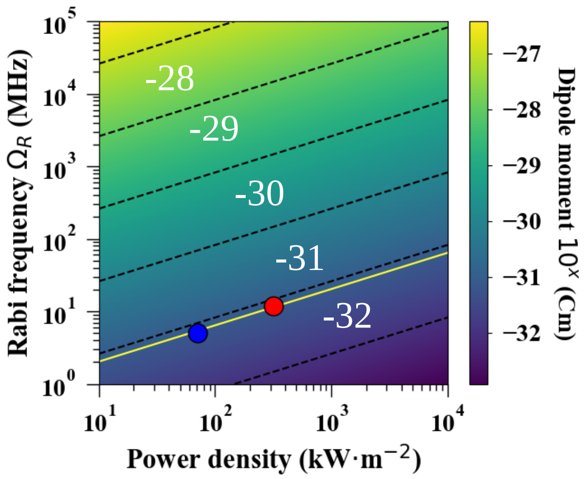

Figure 3. Color plot of dipole moment in the relation between Rabi frequency and pump power: red and blue point indicate calculated dipole moment that we got from the experiments. Yellow line shows the value of dipole moment is 7.8×10^{-32} Cm, the average value of calculated dipole moment.

ground levels with high efficiency in Λ-like system. [9].

4. Conclusions

We were able to observe Rabi oscillations of the transition between hyperfine sublevels in isotopically purified $^{167}Er^{3+}:Y_2SiO_5$ at telecom band. In addition, we measured power dependence of Rabi frequency. The consistency of the calculated dipole moments in each measurement proves observed oscillations of the photoluminescence intensity are in fact Rabi oscillations. This means that we are able to obtain any values of Rabi frequency desired for coherent control. It can contribute to realizing solid-state quantum storage devices that allow for optical coherent manipulation at telecom band.

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