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Population trapping through spectral hole burning in $^{167}Er^{3+}:Y_2SiO_5$

Mark IJspeert[1], Giacomo Mariani[1], Takehiko Tawara[1,2], Kaoru Shimizu[1], Hiroo Omi[1,2], Satoru Adachi[3] and Hideki Gotoh[1]

[1] NTT Basic Research Laboratories, NTT Corporation, Atsugi, Kanagawa 243-0198, Japan
Phone: +81 46 240 3683 E-mail: tawara.takehiko@lab.ntt.co.jp
[2] NTT Nanophotonics Center, NTT Corporation, Atsugi, Kanagawa 243-0198, Japan
[3] Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan

We demonstrate initialisation of the electron population in a Λ-system of $^{167}Er^{3+}:Y_2SiO_5$ through spectral hole burning. Whereas population trapping was observed up to 3 K, the coherence time of the optical transition at 2.4 K was found to be $T_2 = 5.3$ µs, allowing for future research of quantum state manipulation in $^{167}Er^{3+}$-doped solid-state materials at telecom wavelength.

1. Introduction

Rare-earth doped crystals are promising candidates for solid-state quantum storage devices that allow for optical coherent manipulation. The fact that rare-earth ions exhibit narrow optical homogeneous linewidths, approaching the radiative lifetime limit ($T_2 = 2T_1$), highlights their potential as quantum memories [1]. Erbium-doped systems in particular, with an optical transition (~1.5 µm) that coincides with the telecom-band wavelength, offer a platform for the realisation of quantum information networks [2]. Many protocols for storing photons in ensembles of atoms have been proposed, including electromagnetically induced transparency (EIT) [3], photon echo techniques based on controlled reversible inhomogeneous broadening (CRIB) [4] and stimulated Raman adiabatic passage (STIRAP) [5]. Most of these schemes require initialisation of a so-called Λ-system, i.e. a three-level structure with two long lived ground states that can effectively be coupled to an excited state through optical transitions. Secondly, the coherence time T_2 of the optically coupled levels determines the quality of such manipulations. In this work, we estimate the coherence time of an optical transition in $^{167}Er^{3+}:Y_2SiO_5$, whilst demonstrating population trapping through spectral hole burning (SHB) [6], paving the way for storage protocols in $^{167}Er^{3+}$-doped solid-state materials at telecom wavelength.

2. Spectral Hole Burning Scheme

In transmission spectra of SHB, the spectral hole has a Lorentzian shape. Its width Γ_{SHB} depends on the homogeneous linewidth Γ_H of the transition, the normalised pump intensity Ω, the relaxation (T_1) and decoherence (T_2) times in the following way:

$$\Gamma_{SHB} = \Gamma_H\left(1+\sqrt{1+\Omega^2 T_1 T_2}\right), \qquad (1)$$

where $\Gamma_H = (\pi T_2)^{-1}$ [7]. In the low pump intensity limit, $\Omega^2 T_1 T_2 << 1$, so $\Gamma_{SHB} \approx 2\Gamma_H$. For $\Omega^2 T_1 T_2 >> 1$, Eq. 1 reduces to $\Gamma_{SHB} \approx \Gamma_H \Omega (T_1 T_2)^{1/2}$, i.e. the high intensity limit. In order to estimate the coherence time T_2, we analyse the spectral hole width dependence on the pump beam intensity $\Pi \sim \Omega^2$.

The SHB-setup is shown in Fig. 1 [8]. The light source, a CW ECLD, emits at a frequency of 195 THz with a spectral linewidth of 1 kHz. As the beam is split into a pump and probe line, two electro-optic modulators (EOMs) create frequency sidebands. Whereas the pump sideband is fixed at 10.3 GHz, the probe sideband is continuously swept across a set frequency range. To reduce noise, higher-order probe sidebands are suppressed through a band pass filter (BPF). Both pump and probe beams (with mode-field diameters of 200 µm) counter-propagate along the b-axis through 6 mm of the crystal – an isotopically purified $^{167}Er^{3+}$-doped Y_2SiO_5 sample (0.001% $^{167}Er^{3+}$ concentration) kept at a temperature of 2.4 K. In order to eliminate the non-uniform absorption characteristics of the BPF, the probe beam is split into a reference and transmission line, from which the normalised sample transmission can be inferred. Separate femtowatt receivers direct detected signals to a digital phosphor oscilloscope (DPO) that is synchronised with the probe line frequency sweep.

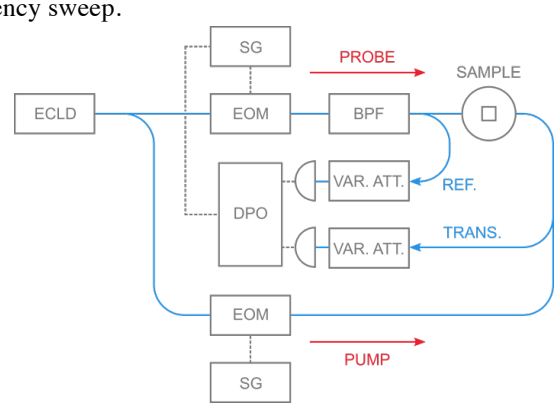

Fig. 1 Electro-optical setup for SHB measurements.

3. Results and Discussions

As can be seen from Fig. 2(a), the normalised transmission curve shows the inhomogeneous broadening of the optical transition. At the pump modulation frequency of 10.3 GHz, we observe a narrow hole (increased transmission), associated with the depleted hyperfine ground state of the Λ-system (see inset Fig. 2(a)). Likewise, the antihole (decreased transmission) appearing at a detuning of 11.18 GHz heralds the presence of an overpopulated hyperfine ground state. The separation of 880 MHz between the hole and antihole positions equals the hyperfine splitting between the two ground states in this Λ-system [9]. To confirm this pop-

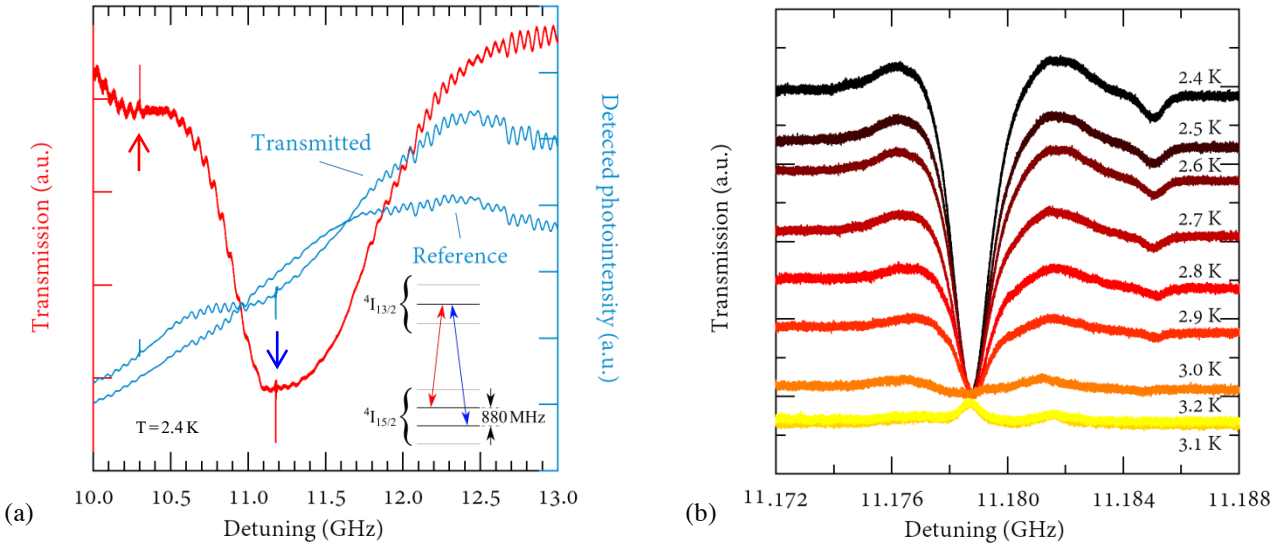

Fig. 2 (a) SHB transmission spectrum as a function of detuning from the central laser frequency of 195 THz (main) and Λ-system structure (inset). The blue curves represent the transmitted and reference signals (see Fig. 1). Arrows indicate the locations of the hole (red) and antihole (blue) and their corresponding energy transitions. Probe frequency sweep range: 10-13 GHz, sweep time: 250 ms, sampling rate: 500 kS/s, number of averaged samples: 2000, DPO resolution: 2 kHz. (b) Temperature dependence of antihole spectra.

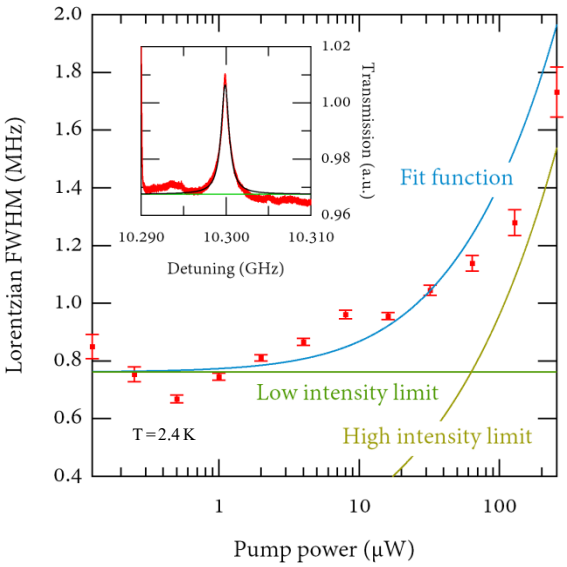

Fig. 3 Hole spectrum with fitted Voigt curve (inset) and pump power dependence of the Lorentzian linewidth extracted from the Voigt curve (main). The solid lines represent the fit function (see Eq. 1) and its two limiting cases.

ulation trapping, we consider the temperature dependence of the antihole spectrum (Fig. 2(b)). As the temperature increases to 3 K, the antihole depth reduces to zero, indicating that this hyperfine ground state is no longer overpopulated due to thermal excitation to higher levels. To estimate the T_2-time of the optical transition, we analysed 12 different hole spectra for increasing pump beam intensities. The Lorentzian linewidths were extracted from the Voigt curves fitting these hole spectra (see Fig. 3). The fit function (Eq. 1) yields $T_2 = 5.3$ μs as an estimate for the coherence time. The low intensity limit breaks down at a pump power of about 2 μW, which corresponds to an intensity of 64 Wm^{-2}.

3. Conclusions

Through spectral hole burning, we have selected a Λ-system in the energy level structure of $^{167}Er^{3+}:Y_2SiO_5$. The existence of an antihole and its temperature dependence indicate that the electron population is trapped in one of the hyperfine ground states. The Λ-system under consideration has thus been successfully initialised. The coherence time of the optical transition was found to be $T_2 = 5.3$ μs. As the basis for quantum state initialisation in $^{167}Er^{3+}:Y_2SiO_5$ has been laid in this research, future work is expected to include the implementation of optical control sequences that will enable quantum state manipulations in $^{167}Er^{3+}$-doped solid-state materials at telecom wavelength.

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