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ScienceDirect
Journal of Luminescence 127 (2007) 94–97
JOURNAL OF LUMINESCENCE
www.elsevier.com/locate/jlumin

Coherent information storage with photon echoes produced by switching electric fields

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Available online 2 March 2007

Abstract

We demonstrate modified photon echoes in Eu^{3+}:Y_2SiO_5 by controlling the inhomogeneous broadening of the $^7F_0 \leftrightarrow {}^5D_0$ optical transition in Eu^{3+}. These modified photon echoes are shown to be capable of storing phase and amplitude modulation.

PACS: 42.50.Md; 42.62.Fi

Keywords: Quantum memory; Photon echoes; Reversible inhomogeneous broadening

1. Introduction

The ability to store and recall quantum states of light is a highly desired operation in the emerging field of quantum information science. A device capable of storing quantum states of light, referred to as a quantum memory, would readily find applications in quantum networks, quantum repeaters and linear optics quantum computing [1–4].

Recently, there has been interest in a proposal for a quantum memory for light based on modified photon echoes [5]. Coherent manipulation and storage of classical light states using standard photon echo techniques date back to the 1980s [6]. Photon echo based experiments, in rare-earth doped materials, have demonstrated the ability to store thousands of pulses per optical spot [7] and do signal processing at gigahertz bandwidths [8]. Photon echoes do experience problems when working with optically thick medium though, such as high spontaneous emission and achieving efficient rephasing. The scheme investigated in this paper achieves optical rephasing via reversible inhomogeneous broadening, rather than intense optical rephasing pulses, and avoids the spontaneous emission problems associated with the π pulse of standard photon echoes.

Reversible inhomogeneous broadening was first used to rephase coherence in a two-level optical system in Ref. [9]. In that demonstration the reversible inhomogeneous broadening was obtained using Stark shifts and macroscopic electric field gradients. The resulting modified photon echo was termed a Stark echo which is analogous to field gradient echoes in NMR [10]. In this paper we expand on the work done previously in Ref. [9] to demonstrate that the Stark echo is capable of storing arbitrary pulse waveforms by storing information encoded in both phase and amplitude modulation. The necessary steps towards employing Stark echoes as a quantum memory are also discussed.

2. Experimental

The optical transition used in this experiment was the $^7F_0 \rightarrow {}^5D_0$ in $^{151}Eu^{3+}$, at 579.879 nm in 0.1 at% Eu^{3+}:Y_2SiO_5. Fig. 1 shows the hyperfine structure of the two electronic singlet states. The transition was excited with linearly polarized light propagating along the C_2 axis of the crystal, with the polarization chosen to maximize the absorption. The length of the crystal in the direction of propagation was 4 mm. The crystal was cooled to below 4 K in a liquid helium bath cryostat. A quadrupole electric field was applied to the sample using four 10 mm long, 2 mm diameter rods in a quadrupolar arrangement as shown in

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0022-2313/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.jlumin.2007.02.034

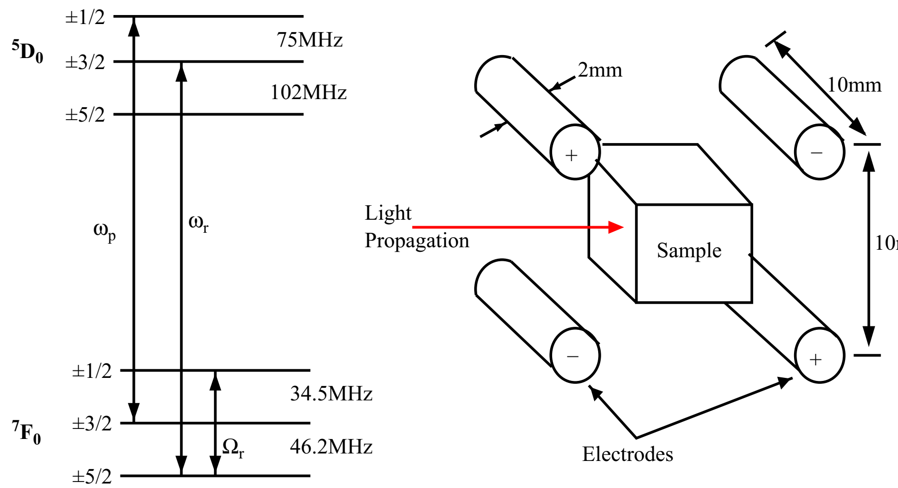

Fig. 1. Energy level diagram of $^{151}Eu^{3+}$:Y_2SiO_5 and the arrangement of the electrodes around the sample. The experiment was carried out on the transition labelled ω_p and ω_r and Ω_r were used to optically pump the desired ions into the $\pm\frac{3}{2}$ hyperfine state.

Fig. 1. Two amplifiers with 1 MHz bandwidth supplied the voltage across the electrodes. These amplifiers had two opposite polarity outputs and voltage rails of ±35 V. This configuration provided an electric field that varied linearly across the sample in the direction of light propagation with a field gradient of approximately 250 V cm^{-2}.

The optical set-up was essentially the same as in previous work [9]. A highly stabilized dye laser was used with an established stability of better than 200 Hz over timescales of 0.2 s. The light incident on the sample was gated with two acousto-optic modulators (AOMs) in series. These allowed pulses with an arbitrary amplitude and phase envelope to be applied to the sample. A Mach–Zehnder interferometer arrangement with the AOMs and sample in one arm was employed to enable heterodyne detection of the coherent emission from the sample, as shown in Fig. 2. The overall frequency shift of ω_p from the local oscillator beam, introduced by AOM1 and AOM2, was 51 MHz. The intensity of this 51 MHz beat signal was detected with a photo-diode.

In order to obtain phase sensitive detection this 51 MHz beat signal was downshifted, after the photo-detector, using a 41 MHz radio frequency (RF) local oscillator and a mixer, to a 10 MHz beat. This 10 MHz beat signal was then combined in a dual double-balanced mixer with a second RF local oscillator at 10 MHz. Two orthogonal outputs of the mixer provided the phase sensitive detection of the Stark echo. These two orthogonal phases were measured and combined to determine the in-phase and the quadrature signals.

The linear Stark shift for the $^7F_0 \rightarrow {}^5D_0$ transition in Eu^{3+}:Y_2SiO_5 has not been reported but from a study in $YAlO_3$ it is expected to be of the order of 35 kHz V cm^{-1} [11]. With the current experimental set-up the anticipated Stark-induced spectral broadening was therefore 2 MHz. Although this broadening is large compared to the 122 Hz homogeneous linewidth of the optical transition it is significantly smaller than the inhomogeneous linewidth of our sample which was 3 GHz. To create an optical feature

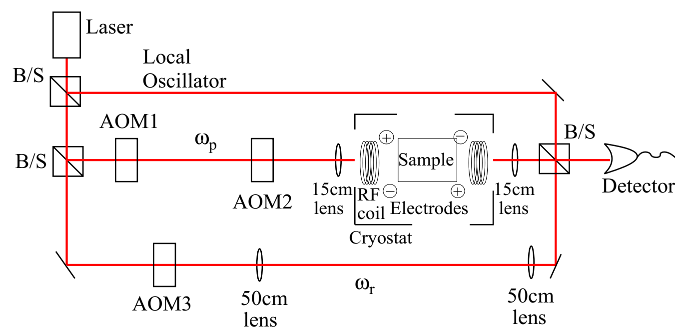

Fig. 2. Schematic of the experimental set-up showing the interferometer and the various beams. Beamsplitters are labelled as B/S. The ω_r and RF coils are used to prepare the ions in the $^7F_0$ $(\pm\frac{3}{2})$ state and are not involved in the detection. The ω_p beam is the probe beam with a frequency shift of 51 MHz from the local oscillator beam.

which was narrow compared to the induced broadening, the same optical pumping procedure as used in Refs. [12,13] was employed. This consisted of burning a relatively wide (≈3 MHz) spectral hole in the absorption line by scanning the laser frequency. A narrow anti-hole was placed in the middle of this region by applying RF excitation at 80.7 MHz as well as light detuned by a combination of hyperfine splittings, as shown in Fig. 1. The spectral width of the anti-hole was then reduced by optically pumping, out of resonance, ions more than 12.5 kHz from the center frequency of the anti-hole. The peak absorption of the feature was approximately 40%.

3. Results and discussion

Fig. 3 shows that we were able to store and then recall four distinct pulses. The input pulses were all 1 μs long with a 3 μs delay between each pulse. The four pulses were absorbed by a 25 kHz wide feature that had been broadened via the application of the electric field. The input pulses appear broader than 1 μs due to saturation of the detector and the limited bandwidth of the detection system.