Light-shift modulated photon-echo

Thierry Chanelière¹ and Gabriel Hétet¹,²
¹Laboratoire Aimé Cotton, CNRS, Université Paris-Sud and ENS Cachan, CNRS-UPR 3321, 91405 Orsay, France
²Laboratoire Pierre Aigrain, Ecole Normale Supérieure-PSL Research University,
CNRS, Université Pierre et Marie Curie-Sorbonne Universités,
Université Paris Diderot-Sorbonne Paris Cité, 24 rue Lhomond, 75231 Paris Cedex 05, France

compiled: January 23, 2015

We show that the AC-Stark shift (light-shift) is a powerful and versatile tool to control the emission of a photon-echo in the context of optical storage. As a proof-of-principle, we demonstrate that the photon-echo efficiency can be fully modulated by applying light-shift control pulses in an erbium doped solid. The control of the echo emission is attributed to the spatial gradient induced by the light-shift beam.

OCIS codes: (020.1670); (160.5690); (160.2900); (210.4680); (270.5565); (270.5585)
http://dx.doi.org/10.1364/XX.99.099999

The photon-echo technique has been reconsidered recently with important applications in the context of quantum information storage and processing [1]. The two-pulse or three-pulse schemes have inspired a variety of storage protocols [2]. The echo techniques have been implemented in different systems from atomic vapors to doped solids with remarkable performances in terms of efficiency [3, 4], bandwidth [5], multiplexing capacity [6, 7]. The two-pulse echo is indeed a stimulating source of inspiration to propose new protocols. In the echo sequence, the classical τ-pulses must be associated with an extra control parameter to make the protocol suitable for quantum storage. This can be a rapidly switched electric field [8, 9], a magnetic field [10, 11], a modified phase-matching condition [12] or a frequency tunable active cavity [13, 14]. These proposals cover different realities, atomic vapors and doped solids, both in the optical or the radio-frequency domain. The AC-Stark shift or light-shift can naturally complete this panorama for materials with a weak or zero sensitivity to the DC-Stark or Zeeman effects as pointed out early by Kraus et al. [9]. As a counterpart of the DC-Stark shift which has already proven to be very efficient for quantum memories based on the so-called gradient echo protocol [4], the light-shift is considered because of its versatility for the gradient design [15] and its fast switching time [16]. The imprinted phase pattern can also apply for optical memories based on “electromagnetically induced transparency” [17]. The light-shift induced by strong laser pulses on spin transitions (electronic and/or nuclear) is also used in spin-echo sequences showing the omnipresence of the phenomenon in different fields [20–22]. Within this general framework, we investigate experimentally the use of light-shift pulses in a standard two-pulse photon-echo sequence. We show that the emission can be fully modulated by applying light-shift pulses. Our demonstration is in that sense equivalent to the DC-Stark shift modulated spectroscopy pioneered by Meixner et al. [23]. In our case, we attribute the modulation to the phase spatial pattern imprinted on the coherences by the light-shift beam. This phase gradient is a starting point to realize an all-optical version of the gradient-echo memory [18, 24]. We first show that the emission of a two-pulse photon-echo (2PE) in Er³⁺:Y₂SiO₅ can be controlled by applying a strong off-resonant pulse. The latter produces a light-shift during the free evolution of the coherences partially inhibiting the echo emission later on. We compensate this extra dephasing by a second light-shift pulse thus validating the method for controlling the emission of an optical memory.

We choose Er³⁺:Y₂SiO₅ as a test-bed because it is recalcitrant to the efficient implementation of the gradient-echo scheme [25]. The experimental setup has been extensively described previously in refs. [20, 27] (see Fig.1).

We implement a 2PE sequence in Fig.2 with a probe beam polarized along D₁ whose waist is 50 μm. We measure its Rabi frequency to be 2π × 150kHz by performing an optical nutation experiment [24]. There is no preparation of the medium by optical pumping. The sequence is repeated every 20ns so the atoms are all initially in the ground state. The 2PE is composed of two gaussian 1μs pulses (rms-duration) separated by t₁₂ = 35μs. The echo is observed at 2t₁₂ = 70μs (Fig.2). A second beam is used to produce off-resonant excitation (light-
Fig. 1. We use a Y$_2$SiO$_5$ sample doped with 50 ppm of erbium cooled down to 1.8 K and with a 2 T magnetic field applied in the plane ($\mathbf{D}_1$-$\mathbf{D}_2$), we obtain as in [27] a coherence time of $\sim 130\mu$s on the $^1\text{I}_{15/2}$ - $^1\text{I}_{13/2}$ transition for the so-called “site 1” [28].

shift pulse) within the echo sequence. The latter has a waist of 110 $\mu$m and is polarized along $\mathbf{D}_2$. We measure its Rabi frequency to be $\Omega_{\text{LS}}^{\text{max}} \simeq 2\pi \times 330\text{kHz}$. It is counterpropagating and overlapped with the probe beam.

Fig. 2. Two-pulse photon echo sequence (dashed black line). We apply two strong pulses at $t = 0$ and $t_{12} = 35\mu$s (clipped by the oscilloscope scale). We observe an echo at $2t_{12} = 70\mu$s. The intensity is normalized so that the echo amplitude is 1. When a light-shift pulse detuned by 1.5MHz (in solid red) is applied at $t_{12}/2 = 17.5\mu$s, the echo intensity (solid black) is reduced from 100% to 30%. Inset: Reduction of the echo intensity as a function of the light-shift intensity $I_{\text{LS}}$ (the dashed line is used to guide the eye). Measurements errors are a few percents given by shot-to-shot fluctuations due to the laser jitter (they roughly correspond to the markers size).

In Fig. 2 we show that when a light-shift pulse whose rms-duration $\tau = 3\mu$s and detuned by $\Delta = 2\pi \times 1.5\text{MHz}$ is applied at $\frac{t_{12}}{2} = 17.5\mu$s, the echo is reduced from 100% to 30%. In Fig. 2 (inset), we also increase gradually the light-shift pulse intensity $I_{\text{LS}}$ from 0 to its maximum value $I_{\text{LS}}^{\text{max}}$ corresponding to $\Omega_{\text{LS}}^{\text{max}}$.

The destruction of the echo by an extra pulse inserted in the time sequence is not obviously attributed to the light-shift induced on the coherence rephasing. Nevertheless it should be noted that the light-shift beam is sufficiently detuned to produce only an off-resonant excitation on the atoms driven by the probe. The probe pulses have a duration of 1$\mu$s so their bandwidth is typically 150kHz very comparable to the Rabi frequency of $2\pi \times 150\text{kHz}$. This is significantly lower than the light-shift beam detuning $1.5\text{MHz}$.

To support our claim we propose to investigate the light-shift dependency as a function of the experimental parameters. If the light-shift pulse is described by its time-varying Rabi frequency $\Omega(t)$, one expects the transition of the atoms under the probe to be shifted by $\frac{\Omega^2(t)}{\Delta}$. The accumulated phase $\Phi_{\text{LS}}$ is then

$$\Phi_{\text{LS}} = \int_0^T \frac{\Omega^2(t)}{\Delta} \, dt = \sqrt{2\pi} \frac{\Omega_{\text{LS}}^{\text{max}} \tau}{\Delta} \quad (1)$$

given by the gaussian pulse parameters, $\Omega_{\text{LS}}$ its amplitude and $\tau$ its duration. We investigate this dependency (Eq. 1) by first varying $\Delta$. The time sequence is the same as before (see Fig. 2) expect that $\tau = 2\mu$s and $\Delta$ is varied from $2\pi \times 1\text{MHz}$ to $2\pi \times 3\text{MHz}$.

Fig. 3. Echo intensity when the light-shift pulse detuning $\Delta$ is varied (square symbols). The experiment is repeated by varying $\Delta$ but by keeping $\tau/\Delta=2\mu$s MHz constant so $\tau$ goes from $2\mu$s to $6\mu$s (circles). The dashed lines are used to guide the eye. Measurement errors are again a few percents.

When $\Delta$ is increased (Fig. 3), the effect of the light-shift pulse is reduced, thus qualitatively following the $1/\Delta$ dependency. A quantitative analysis is not directly possible because a perturbative treatment is inappropriate when strong pulses are used [29]. Alternatively, we propose to vary $\Delta$ but by keeping $\tau/\Delta$ constant to validate Eq. 1. In this latter case, we observe that the effect of the light-shift is quasi-constant. A weak significant variation from 30% to 38% is still observable. It cannot be explained by Eq. 1. Additional modeling would be required. In any case, the influence of the light-shift pulse is in satisfying agreement with the expected $\tau/\Delta$ dependency.

To further explore this effect, we now propose to apply a first phase shift within the sequence and to compensate it by a second pulse. Looking at Eq. 1, an intuitive
compensation solution is to apply two successive pulses with opposite detunings during the free evolution between $t = 0$ and $t_{12}$. A less obvious solution offered by the 2PE sequence is to apply one light-shift pulse between $t = 0$ and $t_{12}$ (called region I) and a second one between $t_{12}$ and $2t_{12}$ (called region II) with the same detuning.

To justify this compensation scheme, we can simply track down the accumulated phase $\phi(\omega, t)$ due to the inhomogeneous dephasing [22]:

- In region I, after the first excitation, the coherence at the frequency $\omega$ freely evolves, accumulating $\phi(\omega, t) = \omega t$. Just before the second pulse at $t_{12}$, the phase is $\phi(\omega, t_{12}) = \omega t_{12}$.
- If a light-shift pulse is applied in region I, an extra term $\Phi^I_{LS}$ is added: $\phi(\omega, t_{12}) = \omega t_{12} + \Phi^I_{LS}$.
- The second pulse conjugates the coherence so the phase is now $\phi(\omega, t_{12}^+ = -\omega t_{12} - \Phi^I_{LS}$ right after the second pulse.
- During the free evolution from $t_{12}$ to $t$ in region II, the accumulated phase is $\omega(t - t_{12})$ so the total phase is $\phi(\omega, t) = -\omega t_{12} - \Phi^I_{LS} + \omega(t - t_{12}) = \omega(t - 2t_{12}) - \Phi^I_{LS}$. As expected, the retrieval time $2t_{12}$ corresponds to the coherence rephasing.
- If a light-shift pulse is applied in region II, an extra term $\Phi^{II}_{LS}$ is added.

Thus the total inhomogeneous phase at the instant of retrieval is

$$\phi(\omega, t) = \omega(t - 2t_{12}) - \Phi^I_{LS} + \Phi^{II}_{LS}. \quad (2)$$

As a conclusion, similar pulses (same detuning) applied in region I and II compensate each other. Pulses with opposite detunings cancels each other only if they are both in region I or II exclusively. This is what we verify in Fig. 4. By properly choosing the sign of the detuning and the region of application, we can retrieve an echo with 98% (Fig. 4a and 4c) of its initial reference intensity.

As a summary, the dependency as $\tau/\Delta$ illustrated in Fig. 3 and the compensation scheme presented in Fig. 4 based on Eq. (2) is a strong evidence that the echo is indeed controlled by the light-shift induced by the off-resonant pulses. This analysis justifies the main claim of our paper. Even if we have shown that the induced light-shift can be used to fully modulate the echo from 100% to 3% (Fig. 4d), a quantitative link between Eq. (1) and the echo amplitude is not obvious. This would require further modeling and is beyond the scope of the present letter. Nevertheless, it is important to note that a net global added phase to all the atoms excited by the 2PE (within the interaction volume and within the inhomogeneous broadening) does not change the echo amplitude but only its phase. The echo is reduced only if the phase varies through the inhomogeneous profile (depends on $\omega$, spectral dependency) or is not constant through the sample (spatial dependency). A spectral dependency may prevent the coherence rephasing. A spatial dependency modifies the phase-matching condition when the echo is emitted. We discuss these two possible effects before concluding.

A spectral dependency induced by the light-shift has a negligible influence in our case because the detuning is significantly larger than the excited bandwidth as previously mentioned. It should be noted that the first order effect of a spectral dependency described by

$$\Phi_{LS}(\omega) = \sqrt{2\pi} \frac{\Omega_{LS}^2}{\Delta} \tau \simeq \sqrt{2\pi} \frac{\Omega_{LS}^2}{\Delta} \tau - \sqrt{2\pi} \frac{\Omega_{LS}^2}{\Delta^2} \tau \omega \quad (3)$$

is to modify the retrieval time from $2t_{12}$ to $2t_{12} \pm \sqrt{2\pi} \frac{\Omega_{LS}^2}{\Delta^2} \tau$ (see Eq. 2 depending if the pulse is in region I or II). The pulse should be delayed to the first order. This is not what we observe so the spectral dependency is certainly negligible.

The spatial dependency of the induced light-shift $\Phi_{LS}(z, r)$ can now be discussed. It may be both longitudinal (along $z$) and transverse (along $r$). The former may be due to the absorption of the light-shift beam $\Omega_{LS}(z)$ along the propagation direction $z$. The latter
appears because the light-shift beam as a finite size (110 \( \mu m \)) with respect to the probe (50 \( \mu m \)). The longitudinal dependency can be evaluated. At \( z = 0 \), we have \( \Omega_{LS}(0) \simeq 2\pi \times 330kHz \) and then \( \Phi_{LS}(0) \simeq 1.1\pi \). If the light-shift pulse was fully absorbed, then it would produce a phase gradient from 1.1\( \pi \) at \( z = 0 \) to 0\( \pi \) at the output of the sample. In other words, the input and the output slice emissions would be out of phase thus explaining the echo reduction (phase mismatch). This appealing explanation is unfortunately extremely unlikely. The medium is absorbing for the light-shift beam which is polarized along \( D_2 \) (optical depth \( \sim 3.5 \)). Nevertheless, the light-shift pulses area is large (\( \sim 7\pi \)) so they are not absorbed as small-area pulses would be \([29]\).

They may exhibit solitonic propagation or self-induced transparency, in any case their amplitude will not go to zero. To verify this statement, we perform 1D-Bloch-Maxwell numerical simulations modeling the echo emission and the light-shift pulse propagation along the propagation dimension thus taking into account the spectral and the longitudinal spatial dependency. Both are insufficient to explain the experimentally observed echo reduction. We only simulate the modified echo retrieval time by \( \sqrt{2\pi \frac{\Omega_{LS}^2}{\Delta}} \) which is not the dominant experimental observation. The transverse spatial dependency is a very likely explanation. A first order estimation of the transverse shift induced by the probe (50 \( \mu m \)) and light shift beam (110 \( \mu m \)) spatial mode mismatch only predicts a 10% echo modulation. 3D-Bloch-Maxwell numerical simulations would be necessary to account for the three-dimensional propagation of the echo. This is beyond our scope.

To conclude, we show that the photon echo emission can be fully modulated by applying off-resonant pulses within the time sequence. The modulation is due the light-shift induced on the atomic coherence. The echo is modified by the transverse spatial phase gradient imprinted by the light-shift beam. It is a powerful and versatile tool to manipulate the emission of quantum atoms. Our demonstration opens up new perspectives for materials with a low Stark or Zeeman sensitivity.

The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union’s Seventh Framework Programme FP7/2007-2013/ under REA grant agreement no. 287252, from the national grant ANR-12-BS08-0015-02 (RAMACO) and from ANR retour post-doctorants ANR-13-PDOC-0024-01 (SMEQUI).

References