

# Collapses and revivals of stored orbital angular momentum of light in a cold atomic ensemble

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We report on the storage of orbital angular momentum of light in a cold ensemble of cesium atoms. We employ Bragg diffraction to retrieve the stored optical information impressed into the atomic coherence by the incident light fields. The stored information can be manipulated by an applied magnetic field and we were able to observe collapses and revivals due to the rotation of the stored atomic Zeeman coherence for times longer than  $15 \mu\text{s}$ .

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Light beams carrying orbital angular momentum (OAM) have attracted an enormous recent interest owing to the possibility of encoding quantum information in a multidimensional state space [1], to their use to excite vortices in Bose-Einstein condensates [2], as well as to a number of others interesting applications [3]. One important family of these beams, the Laguerre-Gaussian (LG) modes of the electromagnetic field [4], possesses wave-fronts dislocation or vortices specified by a topological charge  $m$ , which sets its OAM along the propagation direction as being equal to  $m\hbar$  per photon. The coherent and nonlinear interaction of light beams carrying OAM with atomic systems have been reported previously using different experimental schemes [5, 6, 7, 8, 9]. From the perspective of quantum information processing, the use of multidimensional state space has a promising prospect to achieve higher quantum efficiency [10]. Indeed, entanglement between photons with OAM and a cold atomic ensemble was already reported in [11] and more recently the generation of twin light beams with OAM was achieved via four-wave mixing in a hot atomic vapor [12].

However, further development in this field is strongly conditioned to our capability of reversibly store and manipulate these higher dimensional quantum states of light into long-lived atomic coherences. The light storage (LS) in an electromagnetically induced transparency (EIT) medium [13], which allow us to obtain later information of a previously stored light pulse, is a well understood phenomenon and was originally described in terms of a mixed two component light-matter excitation, called dark state polariton [14]. However, in a simpler alternative picture, LS can be described as being due to the creation of a ground state coherence grating which contains information on the amplitude and phase of an optical field and which survives after the switching off of the incident fields. To date, several experimental observations of this phenomenon were realized in different systems [15, 16, 17, 18, 19, 20]. Recent theoretical and experimental work have also addressed the storage of spatial structures of light beams (images) in atomic vapors

[21, 22, 23, 24]. For instance, a light vortex was stored in a hot vapor for hundreds of microseconds and its robustness against diffusion demonstrated [21]. However, to date the storage and manipulation of superpositions of OAM states into an atomic ensemble, as well as the characterization of the retrieved states, has not yet been achieved.

In this work, we report the storage of superpositions of OAM states as well as its manipulation through an applied transverse magnetic field, which reveals the collapses and revivals of the stored information mapped in the atomic ensemble. Since any quantum protocols would involve necessarily arbitrary multimode coherent superpositions of these quantum states, its storage and manipulation, even in the classical limit, constitute a prove of principle of such requirement. Differently from previous schemes used to store images in thermal atomic ensembles, we employ a delayed backward four-wave mixing (FWM) configuration which allows us to retrieve the stored information in a different direction, thus strongly facilitating its imagery.

For the experiment we used the Zeeman sublevels of the degenerate two-level system associated with the cesium  $D_2$  line cycling transition  $6S_{1/2}(F = 3) \leftrightarrow 6P_{3/2}(F' = 2)$ . The cesium atoms were obtained from a magneto-optical trap (MOT) operating in the closed transition  $6S_{1/2}(F = 4) \leftrightarrow 6P_{3/2}(F' = 5)$  with a recycling repumping beam resonant with the open transition  $6S_{1/2}(F = 3) \leftrightarrow 6P_{3/2}(F' = 3)$ . The atoms were prepared in the state  $6S_{1/2}(F = 3)$  by switching off the repumping beam for a period of about 1 ms to allow optical pumping by the trapping beams via non-resonant excitation to the excited state  $F' = 4$ . The MOT quadrupole magnetic field is also switched off during these optical pumping period. Typically, the measured optical density of the sample of cold atoms in the  $F = 3$  ground state is approximately equal to 3 for appropriate MOT parameters. Three pairs of Helmholtz coils are used to compensate for residual magnetic fields. In Fig. 1 (a), (b) we show a generic  $\Lambda$  three-level system consisting of two degenerate ground states and one excited state

belonging to the corresponding hyperfine Zeeman manifold, coupled with the incident beams at two different instants of time, according to the time sequence showed in Fig. 1-(c) and the beam geometry of Fig. 1 (d). As depicted in these figures, the two incident writing beams, labelled as  $W$  and  $W'$ , have opposite circular polarization and are incident on the MOT forming a small angle  $\theta \approx 3^\circ$ . These beams will therefore excite a ground-state coherence grating into the atomic ensemble. The induced coherence grating is probed by a reading beam  $R$ , which is counter-propagating to the writing beam  $W$  and has a circular polarization opposite to that beam. In the continuous wave (cw) excitation of the ensemble, this corresponds to the well-known backward FWM configuration [25]. For the time sequence shown in Fig. 1(c), the retrieved signal corresponds to the Bragg diffraction of beam  $R$  into the stored coherence grating and as shown below is counter-propagating to the writing beam  $W'$ , with such dipoles obtained from the expression for the slowly varying coherences

$$\sigma_{2,1a}(\vec{r}, t) = \frac{g_R(t)e^{-\gamma t_s}\Omega_R(\vec{r})\Omega_W(\vec{r})\Omega_{W'}^*(\vec{r})}{|\Omega_W(\vec{r})|^2 + |\Omega_{W'}(\vec{r})|^2}, \quad (1)$$

where, according to Fig. 1 (a) and (b) we labelled 2 and 1a the excited state  $|m_F\rangle$  and the ground state  $|m_F - 1\rangle$ , respectively. In this equation,  $\Omega_i(\vec{r})$  represents the Rabi frequency associated with beam  $i$  in an atom at position  $\vec{r}$ , being given then by  $\Omega_i(\vec{r}) = \mu_{a,b}\mathcal{E}_i(\vec{r})e^{i\vec{k}_i\cdot\vec{r}}/\hbar$ , with  $\mu_{a,b}$  the dipole moment between the levels  $a$  and  $b$  coupled by  $\Omega_i$ ,  $\mathcal{E}_i(\vec{r})$  the electric field envelope of beam  $i$ , and  $\vec{k}_i$  its wave-vector. The term  $e^{-\gamma t_s}$  is a consequence of the effective decay of the ground state coherence due to a residual inhomogeneous magnetic field, with  $\gamma$  the decay rate and  $t_s$  the ‘‘storage time’’. Finally,  $g_R(t)$  is a function describing the shape of the light pulse in mode  $D$  retrieved by the read pulse  $R$ :

$$g_R(t) = \frac{e^{-\gamma_1 t} \sinh(\gamma_2 t)}{\gamma_2}, \quad (2)$$

with  $\gamma_1 = \Gamma_{22}/2 + \gamma$ ,  $\gamma_2 = \sqrt{(\Gamma_{22}/2 - \gamma)^2 - 4|\Omega_R|^2}/2$ , and  $\Gamma_{22}$  is the spontaneous decay rate of level 2. In the above equations  $t = 0$  corresponds to the start of the reading pulse. The retrieved pulse shape and its saturation and decay dynamics were extensively studied in Ref. 20.

In our present experiment, fields  $W$  and  $R$  can be well approximated by plane waves exciting the atomic ensemble. On the other hand, since the waist of beam  $W'$  is considerably smaller than the cloud of atoms, the transverse profile of beam  $W'$  is what actually defines the excited-ensemble shape. Taking this into account, the fact that  $\vec{k}_W = -\vec{k}_R$ , and that the intensity of  $W$  is much larger than the one of  $W'$ , the expression for the excited coherence responsible for the retrieved field  $D$  can be well

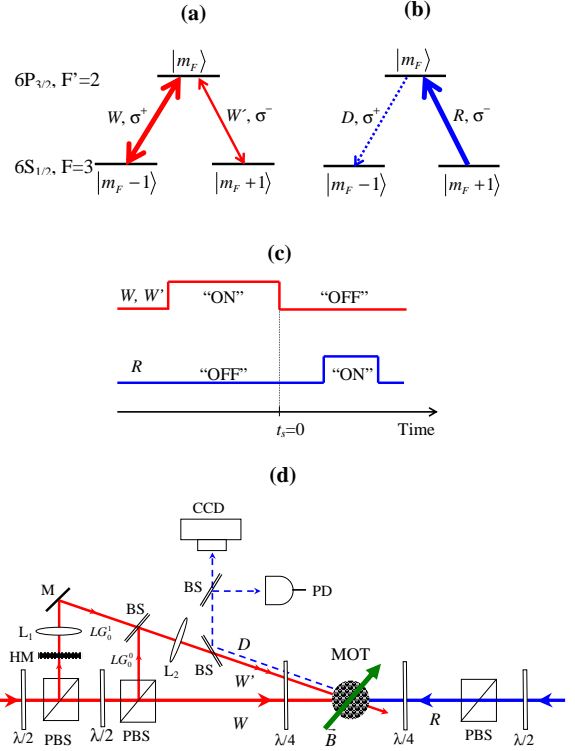


FIG. 1: (a) Generic Zeeman three-level system, showing the coupling with the grating writing beams  $W$  and  $W'$ . Here the beam  $W$  has a much higher intensity than the beam  $W'$ , so the atoms are optically pumped into the highest  $m_F$  level and this level scheme would correspond to  $m_F = 2$ . (b) The coupling of the reading beam  $R$  with the coherently prepared three-level atom, generating the diffracted beam  $D$ . (c) The switching time sequence for the writing and reading beams. (d) Simplified experimental scheme. All the beams are provided by a diode laser locked to the  $F = 3 \leftrightarrow F' = 2$  transition, and are intensity modulated using acousto-optic modulators not shown in the scheme.  $\vec{B}$ : Magnetic field; PBS: Polarizing beam splitter; BS: Beam splitter; HM: Holographic mask; CCD: Camera; PD: Photodetector; L: Lens.

approximated by

$$\sigma_{2,1a}(\vec{r}, t) = A g_R(t) e^{-\gamma t_s} \mathcal{E}_{W'}^*(\vec{r}) e^{-i\vec{k}_{W'}\cdot\vec{r}}, \quad (3)$$

with  $A$  a constant in position and time, depending only on the pumping-beams intensities and the dipole moments of the involved transitions. Equation (3) explicitly indicates that, in our experimental conditions, the  $D$  field propagates in the direction  $(-\vec{k}_{W'})$  opposite to  $W'$ , and have a transverse beam profile given by  $\mathcal{E}_{W'}^*(\vec{r})$ . As we will show, for a Laguerre-Gaussian mode in  $\mathcal{E}_{W'}(\vec{r})$ , this implies that the OAM of the retrieved beam will be inverted with respect to the  $W'$  beam. Equation (3) also shows that the retrieved pulse amplitude decays with a rate determined by the ground-state-coherence lifetime.

We consider now explicitly the case where the incident writing beam  $W'$  contains Laguerre-Gaussian modes with topological charge  $m$ , i.e.,  $LG_0^m$ , described, in polar coordinates  $(r, \phi, z)$  in the plane  $z = 0$ , by a field amplitude  $\mathcal{E}_{W'} \propto (\sqrt{2}r/\omega_0)^m \exp(-r^2/\omega_0^2) e^{-im\phi}$ , where  $\omega_0$  is the minimum beam waist. As shown in Fig. 1 (d), the writing beam  $W'$  can be composed either by a Laguerre-Gaussian mode with a topological charge  $m = 1$ , i.e.,  $LG_0^1$ , generated by the holographic mask  $HM$  and the lens  $L_1$ , or by a zero charge Laguerre-Gaussian mode, or by a superposition of these two modes. These two beams, have approximately the same power of  $20\mu W$  and are focused by the lens  $L_2$  into the MOT with a diameter much smaller than the size of the trapped atomic cloud ( $\approx 2\text{ mm}$ ). The writing beam  $W$  is a simple Gaussian mode ( $LG_0^0$ ), has a power of  $\approx 2.0\text{ mW}$  and a diameter of the order of the trapped cloud. A pair of acousto-optical modulators (AOM) is used to scan the common frequency of the writing beams  $W$  and  $W'$  around the atomic resonance, as well as to allow their fast switching. The reading beam  $R$ , has Gaussian intensity profile, power, and diameter of the same order of beam  $W$ , passing also through another pair of AOM's.

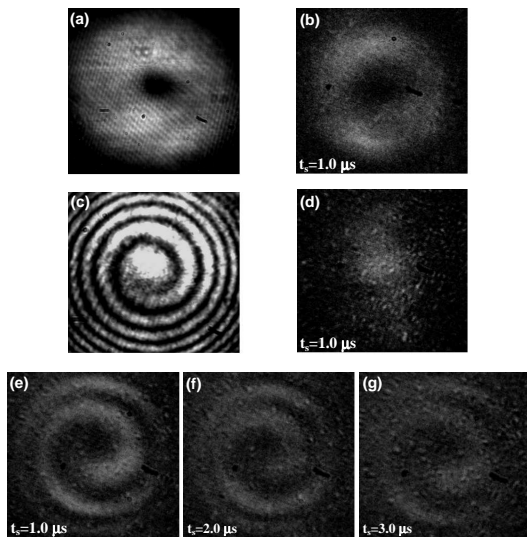


FIG. 2: (a) The incident writing beam intensity profile for the case  $W' = LG_0^1$ ; (b) and (d) The retrieved beam associated respectively with an incident writing beam with modes  $W' = LG_0^1$  and  $W' = LG_0^0$ ; (c) Incident writing beam profile corresponding to a beam superposition  $W' = LG_0^1 + LG_0^0$ . This image is obtained by retro-reflecting the incident superposition right after the MOT. (e), (f) and (g) the retrieved signal corresponding to the incident superposition shown in (c) for the different storage times indicated in the figure. All this set of measurements is obtained without magnetic field.

Under the EIT resonant condition, we have recorded the image of the retrieved beam  $D$  for different incident  $W'$  modes: In Fig. 2 (a) and (b) we show respectively the image of the incident  $W' = LG_0^1$  mode and the image of the corresponding retrieved beam. In order to analyze

the topological charge of the retrieved beam, we consider as a reference wave the diffracted beam associated with a incident Gaussian beam  $W' = LG_0^0$ , whose retrieved profile is shown in Fig. 2 (d). In Fig. 2 (c) we show the image for the incident superposition  $W' = LG_0^1 + LG_0^0$ , obtained by retro-reflecting it with a mirror. In Fig. 2 (e), (f) and (g) we show the corresponding retrieved images obtained for the different storage times indicated in each image. The retrieved signal intensity, as measured simultaneously with the photodetector, decays exponentially with a time constant of approximately  $3\mu s$ , which we attribute mainly to non-compensated magnetic field gradients [20]. Clearly, these images reveal that incident and the retrieved beams have the same single topological charge. However, in order to determine its corresponding sign, we carefully have to take into account that the sense of rotation of the spiral in the interference pattern (which is determined by the sign of  $m$ ) changes upon reflection on a mirror and after passing through a focus [6]. This leads to two consecutive reversions in the sense of the spiral associated with the imagery of the incident  $W'$  superposition. According to the recorded interference patterns shown in Fig. 2 (c) and (e)-(g), we can therefore conclude that the incident and the retrieved beams have the same sign for its topological charge. Moreover, as these two beams propagates in opposite directions they should carry opposite OAM. These observations not only demonstrates that superpositions of OAM states can be stored into the atomic ensemble, but also the reversible transfer of OAM between light and atoms.

In another series of experiments, we applied an external  $dc$  magnetic field of magnitude  $B \approx 0.6\text{ G}$ , nearly orthogonal to the plane defined by the incident beams, and therefore perpendicular to the quantization axis, defined along the beams propagation direction. In this case we observe a series of collapses and revivals of the stored Zeeman coherence as can be seen in Fig. 3, which shows the amplitude of the retrieved signal associated with the input writing beam  $W' = LG_0^1 + LG_0^0$  for different storage times. It is worth noticing that a similar collapses and revivals observation has been reported before and was interpreted as being due to the Larmor precession of the collective spin excitation around the applied magnetic field [27]. Differently from the results presented in Fig. 2, we have observed approximately a four-fold increase in the decay time of the stored coherence grating in the presence of the applied magnetic field. Probably this is associated to a reduced effect of the magnetic field inhomogeneity due to the much stronger applied uniform magnetic field.

For the applied magnetic field, the associated Larmor period  $T_L = 2\pi/\Omega_L$ , where  $\Omega_L = g_F\mu_B B/\hbar$  is the Larmor frequency,  $g_F$  the Lande factor for the lower ground state  $F = 3$  and  $\mu_B$  the Bohr magneton, is  $T_L \approx 5\mu s$  [26]. Thus, revivals of the stored coherence should occur for integer multiples of the Larmor period. Furthermore,

at half the Larmor period the Zeeman coherence and populations are just reversed and therefore we should also expect partial revivals of the retrieved signal for odd multiples of half the Larmor period. These considerations are completely consistent with the series of revivals observed in Fig. 3. We have also recorded

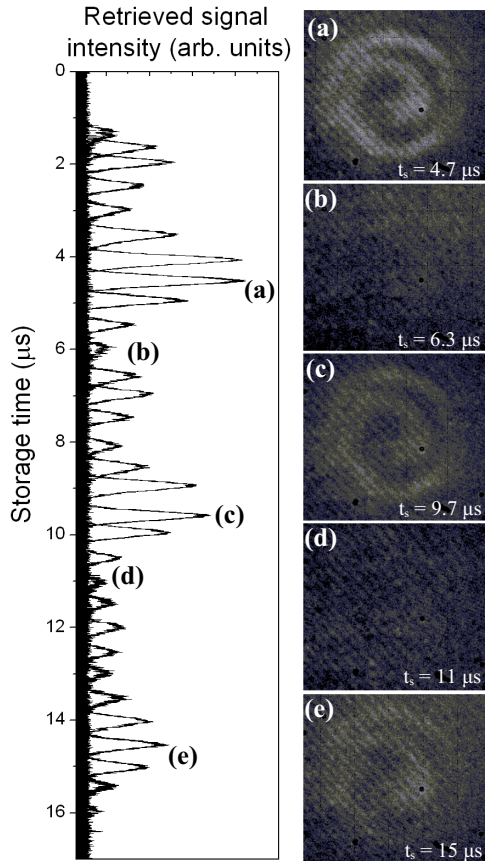


FIG. 3: The amplitude of the retrieved signal associated with a input writing beam  $W' = LG_0^1 + LG_0^0$  for different storage times when a transversal  $dc$  magnetic field is applied. Right column: Retrieved signal intensity profile for the times indicated in the images (a), (c), (e), which correspond to times associated with the first three principal branches of revival peaks; (b) and (d): Frames taken for times corresponding to the indicated collapses times. Note that no images can be seen in these frames.

the images of the retrieved beam for different storage times in the presence of the magnetic field, as shown in the right column of Fig. 3. As indicated, the images (a), (c) and (e) where recorded for storage times corresponding respectively to the first three principal branch of revivals, while images (b) and (d) where recorded for times in the collapse regions, as also indicated in the figure. These results clearly show that the stored collective ground state coherence, containing the information on the superposition of OAM states of the incident beam, can be manipulated by the external magnetic field. To

our knowledge, this constitute the first demonstration of such manipulation of OAM stored in atomic coherences.

In summary, we have experimentally demonstrated the storage of OAM of light in a cold ensemble of cesium atoms, as well as the reversible exchange of OAM between light and atoms. The manipulation of the stored OAM was also demonstrated via Larmor precession of a spatially distributed ground state coherence in an external magnetic field. In particular, collapses and revivals of the stored coherence were directly observed and reveal the control of a collective light-matter excitation. We believe our results fill up one of the gaps challenging the implementation of quantum information processing encoded in a multidimensional state space.

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