Storage of orbital angular momenta of light via coherent population oscillation

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We report on the storage of Orbital Angular Momentum (OAM) of light via the phenomenon of Coherent Population Oscillation (CPO) in cold cesium atoms. The experiment is performed using a delayed four wave mixing configuration where the transverse optical information of a probe field carrying OAM associated with its azimuthal phase dependence is stored in the CPO of Zeeman sublevels of the hyperfine transition $F = 3 \rightarrow F' = 2$ of cesium D$_2$ line. We also demonstrate experimentally the simultaneous storage and retrieval of different OAM states propagating along different directions in space, leading to algebraic operations with OAM and therefore opening the possibility of multiplexing OAM states.

An optical memory, i.e., the possibility of storing information carried by a light beam into an atomic medium for later on demand retrieval, is in the heart of any classical or quantum protocol for processing and manipulating light information [1,2]. Many optical memories are based on the reversible transfer of coherence between light and matter achieved through different physical phenomena such as Electromagnetically Induced Transparency (EIT) [3,4], Gradient Echo Memories (GEM) [5,6], and Atomic Frequency Comb (AFC) [7], which use long-lived ground-state coherence to store the optical information. Recently, a new type of optical memory based on the CPO phenomenon [8–10] has been suggested [11] and then demonstrated [12,13], using intense light fields. The probe absorption spectrum of a driven-two-level atomic system presents CPO resonances around the zero beating frequency, which are associated with the dynamics of atomic level populations. Not based on ground-state coherence, as an EIT-based memory, the CPO memory uses the long relaxation time of the ground state of an open two-level system to store information carried by a light field. In the demonstrated CPO memory, the population oscillation occurs into two open two-level systems coupled by spontaneous emission, where each open two-level system is excited simultaneously by the different field polarization components. Unlike the EIT memory, the insensitivity to magnetic field inhomogeneities makes the CPO-based memory ideal to store spatial information and finds new insights for storing and manipulating orbital angular momentum (OAM) of light.

Light modes with topological charge, Laguerre-Gauss (LG) modes for example, have a spatial dependence through an azimuthal phase given by $e^{i\ell \phi}$ where $\ell$ is an integer, usually called the topological charge. They carry a quantized OAM $\ell \hbar$ per photon [14] and are usable for information processing based on the multidimensional state space spanned by these modes [15]. Optical storage of OAM has been demonstrated previously, both in the classical [16,17] and in the quantum single-photon [18–20] regimes employing the EIT based memories. Recently the storage and retrieval of photonic qubits carrying OAM was also demonstrated [21].

In this Letter we demonstrate the storage and retrieval of OAM of light using the CPO mechanism in an ensemble of cold cesium atoms. This result is the first demonstration of storage and retrieval of the transverse spatial-phase structure of an optical field using this new type of memory. Moreover, we demonstrate the co-storage of two OAM states carried by two optical beams and the retrieval of the sum of the associated topological charges.

The experiment has been performed in cold cesium atoms provided by a magneto-optical trap (MOT) in which two incident beams W, W’ write the information (storage) and another one R reads it (retrieval) according to the backward four-wave mixing (FWM) geometry shown in Fig. 1 (a). The retrieved information is delivered by the diffracted beam denoted by D. The optical memory uses the degenerate two-level system associated with the cesium hyperfine transition $6S_{1/2}(F = 3) \leftrightarrow 6P_{3/2}(F’ = 2)$, as shown in Fig. 1 (b). To prepare the atoms in the lower hyperfine ground state $F = 3$, we switch off the MOT repumping beam 1 ms before switching off the MOT trapping beams. The atomic cloud optical depth is of the order of 4. All the laser beams involved in the experiment are provided by two amplified extended-cavity diode lasers, and are time and frequency controlled using acousto-optics modulators (AOM) in double passage configuration. The MOT magnetic quadrupole field is also turned off during the storing and reading procedures.

In a first experiment, we turn on simultaneously the writing W, W’ and the reading R beams. All the incident beams have approximately the same diameter of the order of 1.2 mm which is smaller than the trapped cloud...
of the CPO memory is, however, much shorter than the expected decay time of 120 μs given by the transit time of the atoms through the $\Lambda = \frac{2\ell}{2\sin(\theta/2)} \approx 25 \mu m$ spatial structure created by W, W’ beams. We attribute this discrepancy to the existence of spurious transversal magnetic field components which can induce transitions between the Zeeman sublevels, therefore decreasing the effective ground state lifetime of the Zeeman sublevels.

In a third experiment, the beams W, W’ have been phase-shaped into LG modes carrying OAM with the respective topological charges $\ell_W$ an $\ell_{W'}$ in order to analyze the CPO memory for OAM beams (Fig. 3 (a)). So, W and W’ are frequency-locked on the $F = 3 \leftrightarrow F' = 2$ transition ($\delta = 0$) in a $\text{lin} \perp \text{lin}$ polarization configuration. The shaping uses the holographic method where an helical phase is imprinted on a Gaussian beam. The hologram is provided by a Spatial Light Modulators (SLM) as described in a previous paper [23] except that we use now two identical SLMs. The diameter of the LG ring has been adjusted to be slightly smaller than the MOT size.

In order to check the topological charge of the W and W’ writing beams or to measure the charge of the retrieved D beam, we used the tilted lens method described in [22]. According to this method, the self-interference pattern of a LG beam with topological charge $\ell$, observed after the astigmatic optics, exhibits $|\ell| + 1$ bright fringes.
turned by an angle whose sign is the sign of \( \ell \). The left column of Fig. 3 (b) shows the self-interference pattern for \( W' \) with the charge \( \ell_{W'} = -2, -1, 0, +1, +2 \). According to FWM phase-matching, for \( \ell_{W} = 0 \), the diffracted beam D acquires the topological charge \( \ell_{out} = \ell_{W'} \), that is illustrated by the right column of Fig. 3(b).

In order to understand these patterns, we note that in the non saturating regime the third-order nonlinear term of the optical polarization, responsible for the generation of the retrieved field, propagating in opposite direction to the beam \( W' \), has an amplitude given by:

\[
\mathcal{E}_D \propto \chi^{(3)} \mathcal{E}_W \mathcal{E}_{W'} \mathcal{E}_R,
\]

where, \( \mathcal{E}_i \), for \( i=W, W', R \) are the amplitude of the incident fields, and \( \chi^{(3)} \) the effective third-order susceptibility of the nonlinear medium. The phase matching implies both the wavevector conservation and the azimuthal phase conservation. The writing beams \( W, W' \) are LG modes with an azimuthal phase given by \( \ell_W \phi \) and \( \ell_{W'} \phi \), respectively and \( R \) is a gaussian mode. Thus, for the considered FWM geometry, the azimuthal phase of \( \mathcal{E}_D \) is \( (\ell_W - \ell_{W'}) \phi \). However, due to wavevector conservation, the D beam counter-propagates \( W' \) and thus its topological charge \( \ell_{out} \) defined relatively to its propagation direction is \( \ell_{out} = \ell_{W'} - \ell_W \). Fig. 3 (b) illustrates this conservation law.

In Fig. 3 (c) we have examined the off-axis OAM retrieval of the CPO memory, by imposing \( \ell_{W'} = 0 \) and \( \ell_W = -2, -1, 0, +1, +2 \). We verify that \( \ell_{out} = -\ell_W \), as it is expected for small OAM values and small angles between \( W \) and \( W' \) [23]. In both cases, on-axis and off-axis retrievals, we have observed that the CPO storage decay time does not depend on the OAM values of the writing beam. It is well known that the fork pattern associated with beams of \( W \) and \( W' \) present a small region, near the center of the LG beam, where the fringes spacing changes as \( \approx \lambda/(\ell + 1)\theta \). With \( \ell = 2 \), the fringes spacing is reduced by a factor 3, reducing the transit time of the atom in this structure by the same factor, so changing the previous expected time to 40\( \mu \)s. This value still rests long compared to the observed CPO storage time. Larger OAM values could, however, affect the storage time.

In another series of measurements we have also performed more complex operations by putting OAM in both writing beams. The results are shown in Fig. 4 for a subset of values of the topological charge, and clearly demonstrates that one can store two OAM values using the CPO-based memory and then retrieve the sum of them. So, for example, starting from OAMs values \( \ell_W = -2 \) and \( \ell_{W'} = 2 \) we have generated \( \ell_{out} = 4 \). The diagonal of Fig. 4 illustrate the case of \( \ell_W = \ell_{W'} \), retrieving a FWM output \( \ell_{out} = 0 \). The non perfect reconstruction of
the topological charge, specifically for the $\ell_{\text{out}} = 0$ case, come from the zero field value at the LG center inducing no FWM at this region. These results, however, are consistent with the conservation law of OAM within the field modes in this delayed FWM process where photons are absorbed from the W and R modes and emitted into the $W'$ and D modes.

In conclusion, we have demonstrated the storage and retrieval of OAM of light through a CPO based memory in cold cesium atoms. A time delayed FWM configuration was employed and the retrieved OAM was shown to be governed by the conservation law of OAM into the incident field modes. We have demonstrated that this memory can be used to perform logical operations involving the stored information encoded in OAM. Our results can be used, for example, to implement a CNOT gate, [24], with memory, using the CPO mechanism. Finally, one may think to extend the CPO memory to the single-photon level, where the single-photon information is transferred to the external degree of freedom of an atom (momentum) and indistinguishably distributed among all the atoms in the ensemble.

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