A quantum memory for orbital angular momentum photonic qubits

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Among the optical degrees of freedom, the orbital angular momentum of light provides unique properties, including mechanical torque action, which has applications for light manipulation, enhanced sensitivity in imaging techniques and potential high-density information coding for optical communication systems. Recent years have also seen a tremendous interest in exploiting orbital angular momentum at the single-photon level in quantum information technologies. In pursuing this endeavour, we demonstrate here the implementation of a quantum memory for quantum bits encoded in this optical degree of freedom. We generate various qubits with computer-controlled holograms, store and retrieve them on demand using a dynamic electromagnetically induced transparency protocol. We further analyse the retrieved states by quantum tomography and thereby demonstrate fidelities exceeding the classical benchmark, confirming the quantum functioning of our storage process. Our results provide an essential capability for future networks exploring the promises of orbital angular momentum of photons for quantum information applications.

The Laguerre–Gaussian (LG) modes belong to a well-studied family of beams carrying orbital angular momentum (OAM). They have a helical phase structure and carry an OAM that can take any integer value. Originating from the solution of the paraxial wave equation in cylindrical coordinates, these modes define an unbounded basis for transverse modes. Because of this infinite dimensionality, the OAM of photons has stimulated intense theoretical and experimental efforts regarding its use for encoding and processing quantum information.

Following the pioneering work demonstrating entanglement in this degree of freedom for photons, great advances have been made in the experimental control of OAM state superpositions and their use in a variety of protocols. These advances include quantum cryptography, bit commitment, experimental quantum coin tossing and, more recently, the demonstration of very high-dimensional entanglement. Beyond their fundamental significance, these ground-breaking experiments testify to the potential of the OAM of light as a quantum information carrier and its promise for enhanced information coding density and processing capabilities. This promise can be extended to applications such as quantum networks, including long-distance quantum repeaters. For such OAM-based implementation, spatial multimode light–matter interfaces will be required.

The ability to store OAM superpositions at the single-photon level in matter systems is of crucial importance for future developments. In recent years, significant progress has been made in this regard through the demonstration of the entanglement of OAM states between a photon and an ensemble of cold atoms or the reversible mapping of bright light beams carrying OAM. Moreover, the preservation of the handedness of the helical phase structure when storing a LG mode has been demonstrated recently at the single-photon level, as has the preservation of the spatial structure for a specific mode superposition. However, to date, no experiment has addressed the capability to store quantum bits, as achieved for instance with other degrees of freedom such as polarization in a variety of physical systems.

Here, we report on the physical implementation of a quantum memory for OAM qubits. Based on a single large ensemble of cold caesium atoms and the dynamic electromagnetically induced transparency protocol (EIT), our device enables us to store and recall superpositions of LG modes of opposite helicities in the single-photon regime. To show the coherence of the process, we developed an interferometer-based characterization system, including spatial mode projectors. This scheme enables us to perform a full quantum tomography of the encoded states. Fidelities after readout of >92% have been achieved, beating the classical benchmark.

The experimental set-up is depicted in Fig. 1. OAM qubits are implemented with weak coherent states with an adjustable mean number of photons per pulse, $\bar{n}$. The qubit basis is defined by the two LG modes $|R\rangle = |LG_{l=0}\rangle$ and $|L\rangle = |LG_{l=1}\rangle$, where $l$ are the radial and azimuthal indices, respectively. These modes are the so-called doughnut modes and exhibit a vanishing intensity in the centre. We initialize the state to be stored by shaping the wavefront with a computer-controlled spatial light modulator (SLM; see Methods).

The qubit is then coherently mapped into a large ensemble of cold caesium atoms prepared in a magneto-optical trap (MOT) with an optical depth of 15 (see Methods). The atomic three-level $A$ system used here involves two hyperfine ground states, $|g\rangle = |6S_{1/2}, F = 3\rangle$ and $|g\rangle = |6S_{1/2}, F = 4\rangle$, and one excited state $|e\rangle = |6P_{1/2}, F = 4\rangle$. All atoms are initially prepared in $|g\rangle$. The qubit field is resonant with the $|g\rangle \leftrightarrow |e\rangle$ transition. The dynamic EIT storage requires an additional control field, resonant with $|g\rangle \leftrightarrow |e\rangle$.

The control and qubit fields, which are orthogonally polarized, are locked in phase and frequency at the caesium hyperfine splitting frequency. They co-propagate in the ensemble with an angle of 1.7°. The control power is 20 $\mu$W, with a waist of 200 $\mu$m, and the qubit field has a waist of 50 $\mu$m.

The storage process consists of sending the qubits into the memory while the classical control beam is on, making the medium transparent and reducing the group velocity. The control beam is then ramped down to zero in 50 ns, resulting in mapping of the qubit into an atomic coherence. Because of the limited delay (200 ns, corresponding to light slowing by a factor of $3 \times 10^4$) arising from the finite optical depth and length of the sample, a fraction of the light leaks out of the sample without being stored (see Supplementary Information Section III), contributing to a lowering of the overall efficiency. When switching the control back on after a user-defined delay, the stored light is re-emitted into the same spatial mode due to a collective enhancement effect.

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We characterize the performance of our memory device by storing a set of input qubits distributed over the Bloch sphere and by performing subsequent quantum tomography of the retrieved states. Reconstructing the density matrix $\hat{p}$ of any two-dimensional state requires three linearly independent measurements, and can be written as

$$\hat{p} = \frac{1}{2} \left( \mathbb{1} + \sum_{i=1}^{3} S_i \hat{\sigma}_i \right)$$

where $\hat{\sigma}_i$ are the Pauli spin operators and $\mathbb{1}$ is the identity matrix. To access the $S_i$ parameters, measurements are performed in the three spatial bases defined by LG modes ($\{(|R\rangle,|L\rangle)\}$ and Hermite-Gaussian modes ($\{|H\rangle = (|R\rangle + |L\rangle)/\sqrt{2}, |V\rangle = (|R\rangle - |L\rangle)/\sqrt{2} \}$ and $\{|D\rangle = (|R\rangle + i|L\rangle)/\sqrt{2}, |A\rangle = (|R\rangle - i|L\rangle)/\sqrt{2}\}$). To this end, we developed a detection scheme based on spatial mode projectors inside an interferometer, as depicted in Fig. 1 and explained in the following.

The mode to characterize is first split on a 50/50 non-polarizing beamsplitter. Each path includes a mode projector based on a blazed fork hologram and a subsequent single-mode fibre. The light is diffracted with high efficiency (>80%) into the first order, resulting in the subtraction of one OAM unit in the so-called ‘right’ path and the addition of one unit in the ‘left’ path. The resulting TEM$_{00}$ light coupled into the subsequent single-mode fibres is thus the projection of the initial mode on the $|R\rangle$ and $|L\rangle$ qubit states. These components are then brought to interfere via a fibre beamsplitter, and the two outputs are detected by single-photon counting modules.

Given the relative phase $\varphi$ of the interferometer, which is scanned and measured via real-time image analysis (see Methods and Supplementary Information Section I), this scheme gives access to the projections on the two rotated bases. Specifically, the count rates on avalanche photodiode APD 1 (respectively APD 2) at phases $\varphi = 0$, $\pi/2$, $\pi$ and $3\pi/2$ provide the qubit components along modes $|V\rangle$, $|D\rangle$, $|H\rangle$ and $|A\rangle$ (respectively $|H\rangle$, $|A\rangle$, $|V\rangle$ and $|D\rangle$). Projections on the qubit basis $\{|R\rangle,|L\rangle\}$ are obtained by blocking alternately the two paths of the interferometer. As an example, Fig. 2 displays the interference fringes obtained on both counting modules when phase $\varphi$ is scanned, after storage and retrieval of the $|A\rangle$ state. The large achieved visibilities, 80% without noise

![Image](https://example.com/image.png)
background correction and 96.5% with correction, confirm the coherence of the storage process.

The set of measured relative probabilities in the three orthogonal bases enables us to reconstruct the density matrix, as is well known for polarization tomography. Figure 3 provides the density matrices for four retrieved qubits, with a storage time of 1 μs and a mean photon number equal to $\bar{n} = 0.6$, well into the single-photon regime. To quantitatively assess the performances of the memory, we compare these states with the ideal qubit states $|\Psi\rangle$ and compute the fidelity $\langle \Psi | \rho | \Psi \rangle$. The values are summarized in Table 1. The average fidelity is 92.5% when using the raw data and reaches 98% when the background noise is subtracted. Let us emphasize that this value is a lower bound of the achieved storage fidelity as it includes any imperfections in the mode preparation.

To conclude about the quantum character of the demonstrated storage and retrieval process, the fidelities have to be compared with the best achievable using a classical memory protocol, which consists in measuring the state, storing the results classically, and preparing a new state based on these data. This technique, known for instance as the intercept–resend attack in quantum cryptography, can achieve a maximum fidelity of $(N + 1)/(N + 2)$ for a state containing $N$ photons, leading to the well-known 2/3 limit for a single photon. In our case, as the experiment is performed with weak coherent states, the Poissonian statistics has also to be taken into account, resulting in a weighted average depending on the mean photon number per pulse, $\bar{n}$. It can be shown, furthermore, that the non-unity efficiency $\eta$ of the storage and retrieval process can also increase the maximally achievable classical fidelity. By explicitly taking into account these two parameters, ref. 21 provided a fidelity threshold (see also ref. 22), showing that the quantum character of a memory can indeed be assessed with weak coherent states (formulae are provided in the Supplementary Information Section II). This threshold approaches unity when $\bar{n}$ is increasing, thereby critically requiring the device to be tested with coherent pulses with a low mean photon number.

Figure 4 presents the achieved average fidelities (raw and background-corrected) as a function of the mean photon number $\bar{n}$, together with the aforementioned classical limits. The pink shaded region corresponds to the boundary, taking into account the measured storage and retrieval efficiency $\eta = 15 \pm 2\%$. Our results beat the classical limit by several standard deviations for a large range of mean photon numbers, confirming the quantum character of our device. For a very small value of $\bar{n}$, the fidelity drops due to the background noise.

The memory time of our MOT-based system is currently 15 μs, as limited by inhomogeneous Zeeman broadening due to the residual magnetic field and motional dephasing resulting from the angle between the control and signal fields (see Supplementary Information Section III). Further cooling of the atoms and optical pumping into $|F = 4, m_F = 0\rangle$ would readily improve the memory.

### Table 1 | Fidelities of the readout states for six input qubits without and with background noise subtraction.

| Input mode | Raw fidelity (%) | Corrected fidelity (%) |
|------------|-----------------|-----------------------|
| $|R\rangle$ | 95.1 \pm 0.5 | 99.3 \pm 0.5 |
| $|L\rangle$ | 90.0 \pm 0.8 | 97.7 \pm 0.6 |
| $|V\rangle$ | 90.3 \pm 1.1 | 98.8 \pm 0.5 |
| $|D\rangle$ | 94.0 \pm 0.9 | 98.7 \pm 0.5 |
| $|H\rangle$ | 94.7 \pm 0.9 | 98.1 \pm 0.5 |
| $|A\rangle$ | 90.6 \pm 1.1 | 96.2 \pm 0.8 |

The mean photon number per pulse is $\bar{n} = 0.6$. Errors were estimated assuming Poissonian statistics and taking into account phase binning and residual error on the calibration of the interferometer.

### Figure 3 | Quantum tomography of the retrieved OAM qubits.

Reconstructed density matrices for the four input states $|R\rangle, |L\rangle, |H\rangle = |R\rangle + (L)/\sqrt{2}$ and $|D\rangle = |R\rangle + |L\rangle)/\sqrt{2}$. The mean number of photons per pulse here is $\bar{n} = 0.6$, and no background correction has been applied. The first column displays, for each state, its location in the Bloch sphere, the phase pattern imprinted by the SLM, and the associated spatial mode.

### Figure 4 | Average fidelities of the retrieved qubits and quantum storage.

The state fidelity, averaged over the six input qubits, is given as a function of the mean photon number per pulse $\bar{n}$. The purple points correspond to raw data, and the green ones are corrected for background noise. The blue dotted line gives the classical limit for a memory with unity storage and readout efficiency and the red line shows the classical limit for the actual efficiency of our memory device (the pink shaded area represents the error bar on the efficiency). Vertical and horizontal error bars indicate the standard deviations of fidelities and mean photon numbers for the six input states, respectively.
time around 100 µs, as limited by the loss of atoms from the excitation region. To achieve larger values, as required for practical quantum networking applications\textsuperscript{44}, other trapping techniques have to be implemented, enabling optical storage in the second range as demonstrated for instance in light-shift compensated optical lattices\textsuperscript{51}. OAM qubit storage in rare-earth-ion doped crystals\textsuperscript{6} would also be of great interest, with potential long storage times and without the possible issue of the transverse size limitation in an optical lattice.

In summary, we have experimentally demonstrated the operation of a faithful quantum memory for qubits encoded in the OAM degree of freedom and based on a single atomic ensemble. Due to the intrinsic spatial multimode nature of the storing medium, no dual rail implementation with spatially separated ensembles is required, as is usually done for the polarization degree of freedom. We have shown that our device operates better than any classical counterpart, providing a unique tool for investigating quantum networking protocols with this encoding that holds much promise for achieving an increase in information coding density. Given the parameters of our atomic ensemble and the scaling of LG beam size in $\sqrt{T}$, the capacity of our spatial multimode memory can be estimated at around 100 qubit modes\textsuperscript{32}. Future developments of the work presented here include the demonstration of the reversible mapping of OAM entanglement between remote units and the extension of the storage capability to higher OAM values, the manipulation of which can benefit greatly from recent developments in OAM sorting techniques.

Methods

Experimental sequence. The experiment was conducted in sequences, with a repetition rate of 66 Hz, each including a stage for the atomic cloud to build up (11.5 ms for MOT loading and 850 µs for further cooling by optical molasses) and a stage for memory operations (3 ms). To avoid inhomogeneous Zeeman broadening, the magnetic field gradient was switched off after MOT loading, and residual magnetic fields were measured using microwave spectroscopy and compensated down to 5 mT. The memory trials (writing, storage and retrieval) were repeated 200 times per MOT cycle, with a period of 5 ms. Photons were detected by APDs (SPCM-AQR-14-FC) and recorded with a time resolution of 10 ns.

OAM qubit generation. The optical qubits were implemented with weak coherent states at the single-photon level, temporally shaped by an acousto-optic modulator to a half-gaussian profile with a typical width of 300 ns. The phase structure was imprinted by reflection on a computer-controlled pure-phase SLM (Hamamatsu LCOS-SLM X10468-02) with a resolution of 792 x 600 pixels. Examples of phase pattern settings are given in Fig. 1 in false colours. The $|R\rangle$ and $|L\rangle$ modes (that is, LG modes) were generated with a rotating phase pattern and the different superpositions (that is, Hermite-Gaussian modes) with a $\pi$ phase jump pattern.

Accessing the interferometer phase. The interferometer phase $\varphi$ was measured by sending backward a phase-reference beam (nW level). The light was detected on a digital camera at the second output of the first beamsplitter (Fig. 1). On one path, one unit of OAM was added, and on the other path, one unit was subtracted. Recombination of the two resulting LG modes with opposite helicities led to a Hermite-Gaussian mode, with its orientation given by half the relative phase $\varphi$. Images were recorded at a rate of 8 Hz, thus averaging over a few MOT cycles. A single computer triggered the experiment, and recorded the APD events and images. This associated a timestamp to both events and images. Using this timestamp and a Python-written routine to automatically detect the orientation of the images on the camera, a relative phase $\varphi$ was associated to each event. The relative phase was discretized into 60 bins of $6^\circ$ each. To avoid light returning to the APDs, the reference beam was sent only during the MOT building stage when the APDs were gated off.

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Author contributions
L.G., L.V., E.G. and J.L. planned the initial experimental set-up for light–matter interfacing, which was constructed by L.G., L.V. and J.L. All authors contributed to the OAM experiment. A.N., L.V. and D.M. designed the generation and characterization system and performed the measurements and data analysis under the supervision of J.L. All authors contributed to discussing the results. J.L., A.N., L.V. and D.M. wrote the manuscript.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.L.

Competing financial interests
The authors declare no competing financial interests.