

Cavity optomechanical quantum memory for twisted photons using a ring Bose-Einstein condensate

Nilamoni Daloi^{1,*}, Rahul Gupta^{2,*}, Aritra Ghosh^{1,3}, Pardeep Kumar^{4,§}, Himadri S. Dhar^{2,5} and M. Bhattacharya¹

¹*School of Physics and Astronomy, Rochester Institute of Technology, Rochester, New York 14623, USA*

²*Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India*

³*School of Basic Sciences, Indian Institute of Technology Bhubaneswar, Khurda, Odisha 752050, India*

⁴*Max Planck Institute for the Science of Light, Staudtstraße 2, D-91058 Erlangen, Germany*

⁵*Centre of Excellence in Quantum Information, Computation, Science and Technology, Indian Institute of Technology Bombay, Mumbai 400076, India*



(Received 14 June 2025; accepted 15 December 2025; published 9 January 2026)

We theoretically propose a photonic orbital angular momentum quantum memory, currently of great interest from the perspective of quantum networks, based on a ring-trapped Bose-Einstein condensate interacting with Laguerre-Gaussian beams. The optical states are stored in the large Hilbert space of topologically protected persistent currents of the condensate. In contrast to earlier work, our proposal uses a cavity, which enhances the light-matter interaction by several orders of magnitude, resulting in high fidelity, convenient detection, and no need to repeat read-write cycles degraded by atom loss. Our scheme avoids using multiple internal atomic states as in generic electromagnetically induced transparency-based protocols and thus bypasses problems like off-resonant photoassociation by the control fields and dephasing effects that limit memory storage time. For optimized parameters, our work yields a storage time 3 orders of magnitude better than presently available and opens the way for exploiting existing advantages of cavity-based noise suppression, wavelength transduction, large bandwidth, and nondestructive readout of the memory.

DOI: [10.1103/zd1d-39d7](https://doi.org/10.1103/zd1d-39d7)

I. INTRODUCTION

Photonic quantum memories [1–3] are essential components of quantum information networks, designed to store and retrieve quantum states of light on demand. In recent years, the orbital angular momentum (OAM) of photons has attracted significant attention as a high-dimensional basis for encoding quantum information, owing to its unbounded Hilbert space [4]. Existing quantum memory protocols for OAM-encoded photons have primarily relied on cold atomic ensembles [5] via electromagnetically induced transparency (EIT) [6–11], or on rare-earth-ion-doped crystals [12]. The longest reported storage time for a single photon carrying OAM is 400 μ s, achieved using a cold rubidium atomic ensemble [13].

In this context, it is crucial to note that a Bose-Einstein condensate (BEC) [14] confined in a ring-shaped optical trap

[15,16] supports quantized rotation in the form of persistent currents [17–20]. These circulating matter waves are topologically protected and metastable, exhibiting long lifetimes lasting up to a minute [21,22]. Thus, mapping photonic quantum states onto such atomic persistent current modes presents a promising route toward realizing long-lived OAM quantum memories. Earlier theoretical work on such a possibility relied on free-space light-matter interactions and multiple internal atomic states for storage and retrieval in the condensate [23]. While these theoretical proposals date back to two decades, no experiment has thus far demonstrated single-photon information storage and retrieval from a rotating BEC. In practice, the weak free-space light-matter coupling is the main hurdle faced by experimental implementations; even in non-OAM systems, this has required repeated read-write cycles degraded by atom loss from the condensate [24]. However, the use of multiple internal atomic states, mandated by the standard EIT-based protocol [25], also results in off-resonant photoassociation by the control fields [24], as well as dephasing effects that limit the memory storage time [5].

In this article, we propose a quantum memory platform that removes these obstacles: a cavity ring BEC system for the storage and retrieval of photonic states encoded in the OAM basis of light. The persistent currents of the condensate offer a large Hilbert space of states whose topological protection leads to an improved storage time. Further, the cavity significantly enhances the light-matter interaction, leading to high fidelity, and provides well-defined modes for reading and

* These authors contributed equally to this work.

† Contact author: nilamoni123@gmail.com

‡ Contact author: rahul.quantumfield@iitb.ac.in

§ Contact author: pardeep.kumar@mpl.mpg.de

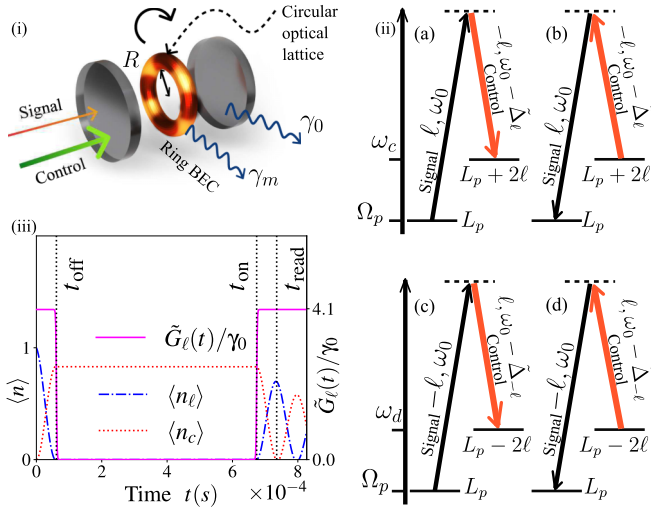


FIG. 1. (i) BEC rotating in a ring trap of radius R , inside a Fabry-Pérot cavity, driven by control and signal fields each in a coherent superposition of LG modes carrying OAM $\pm\ell\hbar$. (ii) Subpanels (a), (b) and (c), (d) show the energy and OAM selection rules for storage and retrieval of a single signal photon with OAM $+\ell\hbar$ and $-\ell\hbar$, respectively. (iii) Read and write protocol for $\ell\hbar$ OAM mode. Parameters used for panel (iii) are as follows: control power $\sim 8.6 \times 10^{-7}$ mW [29], $R = 10 \mu\text{m}$ [22], $L_p = 20$ [30], $\ell = 130$ [4], $N = 2 \times 10^4$ [22], $\gamma_0/2\pi = 1 \text{ kHz}$ [31], $\gamma_m \sim 1.7 \times 10^{-5}\gamma_0$ [22], $\tilde{G} = 4\gamma_0$, $t_{\text{off}} = \pi/2\tilde{G} \sim 61 \mu\text{s}$, $t_{\text{on}} \sim 674 \mu\text{s}$, and $t_{\text{read}} \sim 735 \mu\text{s}$.

writing. Finally, our scheme operates with the atoms always in the same internal state and thus avoids the EIT-based problems enumerated above. Specifically, our platform supports storage of single-photon Fock states carrying OAM of either sign [26], coherent superpositions of counterrotating OAM states [13], and entangled two-photon states with equal and opposite OAM [5]. For optimized experimental conditions, we show that storage times reaching hundreds of milliseconds are achievable, representing 3 orders of magnitude improvement over existing capabilities [13] and beating the classical limit for fidelity [27].

II. THEORETICAL MODEL

We consider a BEC of N identical two-level ^{23}Na atoms of mass m , confined in a ring trap [15] of radius R , placed inside a Fabry-Pérot cavity of length L , resonance frequency ω_0 , and photon decay rate γ_0 , as illustrated in Fig. 1(i). The cavity is driven through one of the mirrors by two optical fields: a strong classical control laser with frequency ω_L and pumping rate ε_c and a weak quantum signal laser of frequency ω_p and pumping rate ε_p . Both fields are prepared in coherent superpositions of Laguerre-Gaussian (LG) [28] modes carrying OAM $\pm\ell\hbar$, generating a circular optical lattice about the cavity axis that overlaps with the ring-shaped BEC, as shown in Fig. 1(i). The BEC undergoes quantized rotational motion around the cavity axis, characterized by a winding number $L_p \in \mathbb{Z}^+$ [18], order parameter $e^{iL_p\phi}$, and rotational energy $\hbar\Omega_p$, where $\Omega_p = \hbar L_p^2/2I$ [29] with $I = mR^2$ being the moment of inertia of an atom of mass m about the cavity axis.

The optical lattice formed by the control field causes Bragg scattering of atoms in the BEC from their initial rotational mode with winding number L_p to side modes with winding numbers $L_p \pm 2n\ell$ ($n = 1, 2, \dots$). The optical fields are blue detuned far from the atomic resonance, making the light-atom interaction very weak. Thus, only first-order Bragg scattering ($n = 1$) is appreciable, and the majority of atoms remain in the mode L_p . Under these conditions, the system Hamiltonian in the rotating frame of the control field is given by (see the Supplemental Material [32] for details)

$$\begin{aligned} H/\hbar = & -\tilde{\Delta}a^\dagger a + \omega_c c^\dagger c + \omega_d d^\dagger d + G(X_c + X_d)a^\dagger a \\ & + i(\varepsilon_c a^\dagger - \varepsilon_c^* a) + i(\varepsilon_p a^\dagger e^{-i\delta t} - \varepsilon_p^* a e^{i\delta t}) \\ & + 4\tilde{g}N(c^\dagger c + d^\dagger d) + 2\tilde{g}N(cd + c^\dagger d^\dagger). \end{aligned} \quad (1)$$

Here, a denotes the annihilation operator for the intracavity field, while $c(d)$ and $X_{c(d)}$ represent the annihilation and position quadrature operators, respectively, for the BEC side mode with winding number $L_p + (-)2\ell$. The energy of the mode $c(d)$ is given by $\hbar\omega_{c(d)}$, where $\omega_{c(d)} = \hbar[L_p + (-)2\ell]^2/2I$. These energies represent the quadratic winding number dependence typical of particlelike Bogoliubov excitations, i.e., single atoms that occupy the persistent current condensate modes $e^{i(L_p \pm 2\ell)\phi}$ [29]. We note that though the energy of rotational excitations exceeds the transverse trap excitation quanta ($\omega_{c,d} > \omega_{\rho,z}$), the trap is sufficiently homogeneous that the rotation remains stable [33]. The parameter G [29,34] denotes the effective optomechanical coupling rate. For the parameters considered in this work, the effective detuning of the control laser from cavity resonance is given by $\tilde{\Delta} \approx \omega_L - \omega_0$. The two-photon detuning is defined as $\delta = \omega_p - \omega_L$. The final two terms in the Hamiltonian account for interatomic interactions, with interaction strength characterized by $\tilde{g}$ [29]. For typical parameters, the effect of weak interatomic interactions is small and Eq. (1) reduces to the canonical optomechanical Hamiltonian [29,34]. The effects of atomic interactions have been briefly discussed in the Supplemental Material [32].

III. QUANTUM MEMORY

Below, we characterize the proposed quantum memory by evaluating its performance for key quantum states, including single-photon Fock states with OAM, coherent superpositions of counterrotating modes, and entangled two-photon states with equal and opposite OAM.

A. Photons with OAM $+\ell\hbar$

The procedure to store a single-photon Fock state with OAM $+\ell\hbar$ in the cavity-BEC setup of Fig. 1(i) follows the energy level diagrams in Figs. 1(ii) (a) and 1(ii) (b) and implements the standard optomechanical memory protocol [35], extended to conserve OAM. The control laser, with OAM $-\ell\hbar$ and frequency ω_L , is red detuned from the cavity resonance ω_0 by the frequency gap between the two BEC modes with winding numbers L_p and $L_p + 2\ell$, respectively. This detuning is given by $\tilde{\Delta}_\ell = -(\omega_c - \Omega_p) \approx -\omega_c$, as $\Omega_p \ll \omega_c$ for typical parameters used in this work. The signal laser, carrying OAM $+\ell\hbar$ and at frequency ω_p , is tuned to cavity resonance ω_0 , with the two-photon detuning $\delta = \omega_p - \omega_L = \omega_c + 4\tilde{g}N$. For

the chosen parameters, $\omega_c \gg 4\tilde{g}N$, making $\delta \approx \omega_c$. At the end of storage, the signal photon quantum state is transferred to a long-lived excitation of energy $\hbar\omega_c$ that serves as the memory. To retrieve the stored state, the control laser is turned back on with the same red detuning, thereby absorbing the phonon and regenerating the signal photon. Similarly, storage and retrieval of a signal photon with OAM $-\ell\hbar$ require the phonon modes L_p and $L_p - 2\ell$, and a control photon with OAM $+\ell\hbar$ [Figs. 1(i) (c) and 1(i) (d)]. In this case, the control field detuning is given by $\tilde{\Delta}_{-\ell} = -(\omega_d - \Omega_p) \approx -\omega_d$ and the two-photon detuning by $\delta = \omega_d$.

Next, we outline the modifications to the Hamiltonian in Eq. (1) required to implement the above protocol. In the weak signal limit ($\varepsilon_c \gg \varepsilon_p$) and the resolved sideband regime ($\omega_{c(d)} \gg \gamma_0$), the intracavity field mode can be decomposed as $a = \alpha + \tilde{a}e^{-i\delta t}$ [36,37], where $\alpha = \langle a \rangle$ denotes the classical amplitude of the strong control field and $\tilde{a}$ the quantum signal field mode. Similarly, the atomic side modes are expressed as $c = \beta_c + \tilde{c}e^{-i\delta t}$ and $d = \beta_d + \tilde{d}e^{-i\delta t}$, where $\beta_{c(d)} = \langle c(d) \rangle$. To suppress crosstalk between c and d modes, we further assume $|\omega_c - \omega_d| \gg \gamma_0$, allowing adiabatic elimination of the off-resonant BEC mode. Under these conditions, the Hamiltonian in Eq. (1) for storing the $+\ell\hbar$ OAM state linearizes to (for details, see the Supplemental Material [32])

$$H_\ell/\hbar = -\Delta' \tilde{a}^\dagger \tilde{a} + \omega_c \tilde{c}^\dagger \tilde{c} + (\tilde{G} \tilde{a}^\dagger \tilde{c} + \tilde{G}^* \tilde{a} \tilde{c}^\dagger), \quad (2)$$

where $\tilde{G}(t) = \alpha(t)G/\sqrt{2}$ is the equivalent boosted optomechanical coupling constant and $\Delta' = \tilde{\Delta}_\ell - G\sqrt{2}\Re[\beta_c + \beta_d]$ is an effective detuning. For typical parameters, the second term of Δ' is negligible ($\Delta' \approx \tilde{\Delta}_\ell$). For brevity, we denote $\tilde{a}$, $\tilde{c}$, and $\tilde{d}$ as a , c , and d , respectively. Without loss of generality, we fix the phase of the control field such that $\tilde{a} \in \mathbb{R}$, and consequently, $\tilde{G} \in \mathbb{R}$. Under transformation, $U = \exp[-i\delta t a^\dagger a] \otimes \exp[-i\delta t c^\dagger c]$ and $\tilde{\Delta}_\ell = -\delta$, Eq. (2) reduces to $H_\ell \sim \hbar\tilde{G}(a^\dagger c + ac^\dagger)$. For the conditions discussed above, only the $+\ell\hbar(-\ell\hbar)$ OAM component is transferred to the mode $c(d)$. Thus, we may write, $H_\ell \sim \hbar\tilde{G}(a_\ell^\dagger c + a_\ell c^\dagger)$.

For numerical simulation, we solve the following Lindblad equation [38]:

$$\dot{\rho} = \frac{1}{i\hbar}[H_\ell, \rho] - \frac{\gamma_0}{2}\mathcal{D}[a_\ell]\rho - \frac{\gamma_m}{2}\mathcal{D}[c]\rho, \quad (3)$$

where ρ is the density matrix for the cavity-BEC system, γ_m is the damping rate of the atomic mode, and $\mathcal{D}[\mathcal{O}]\rho = \{\mathcal{O}^\dagger \rho, \mathcal{O}\} - 2\mathcal{O}\rho\mathcal{O}^\dagger$. Experimentally relevant parameter values have been used, which satisfy the physical constraints described thus far in the paper. After solving Eq. (3), the density matrix of the optical signal is obtained by tracing out the BEC mode. The time dynamics of the simulation for writing and reading the state $|1\rangle_\ell$ are shown in Fig. 1(iii). Since H_ℓ resembles a beam-splitter-type interaction, it coherently swaps the quantum states of modes a_ℓ and c with a period $\pi/2\tilde{G}$. Thus, a state initialized in a_ℓ at $t = 0$ is transferred to c after that duration. Turning off the control field at this time (t_{off}) effectively stores the quantum state in c [Fig. 1(iii)]. Optimal readout is achieved by reactivating the control field at t_{on} and measuring the output at $t_{\text{read}} = t_{\text{on}} + \pi/2\tilde{G}$.

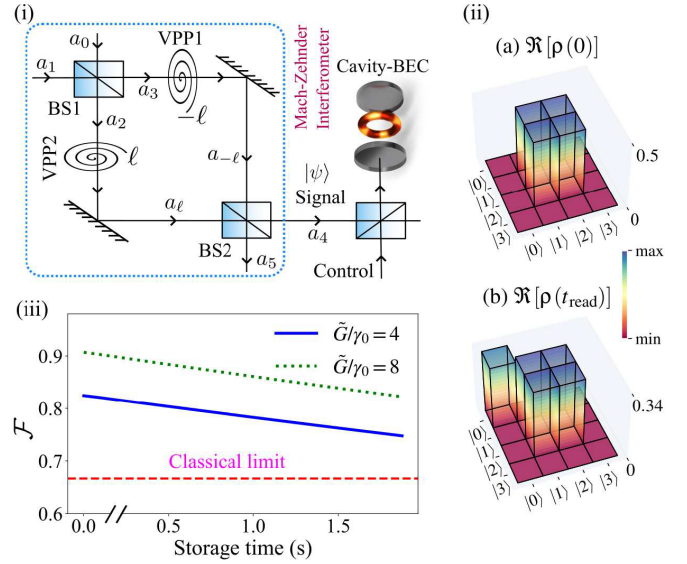


FIG. 2. (i) Schematic for generating an OAM superposition state. The beam splitters and vortex phase plates are denoted by Beam Splitter (BS) and Vortex Phase Plate (VPP), respectively. The optical modes are denoted by a_i , $i \in (0 - 5)$. (ii) (a) Initial density matrix for $|\psi\rangle$ of Eq. (5) and (b) retrieved density matrix. (iii) Retrieval fidelity ($\mathcal{F}$) vs storage time (~ 0.6 to 1.9 s) for different values of $\tilde{G}/\gamma_0$. The red dashed line at $2/3$ in panel (iii) shows the classical limit of fidelity. Parameters for panel (ii) are the same as in Fig. 1.

B. Superposition of OAM $\pm\ell\hbar$ states

We now consider the storage of a coherent superposition of the OAM state of light given by $|\psi\rangle = (|\ell\rangle + |-\ell\rangle)/\sqrt{2}$. This state can be created using a Mach-Zehnder interferometer as shown in Fig. 2(i); a brief analysis of the scheme is provided in the Supplemental Material [32,39]. In our scheme, two control fields with detunings $\tilde{\Delta}_{\ell(-\ell)} = -\omega_{c(d)}$ are used to mediate the storage of $|\ell(-\ell)\rangle$. The linearized Hamiltonian governing the dynamics is given by

$$H_{\text{sup}}/\hbar = \tilde{G}_\ell(a_\ell^\dagger c + a_\ell c^\dagger) + \tilde{G}_{-\ell}(a_{-\ell}^\dagger d + a_{-\ell} d^\dagger), \quad (4)$$

where $a_{\ell(-\ell)}$ denote the annihilation operators for the $|\ell(-\ell)\rangle$ OAM components of the signal mode and $\tilde{G}_\ell = \tilde{G}_{-\ell}$ are the corresponding boosted coupling constants.

In the formalism of second quantization, the superposition state $|\psi\rangle$ reads [40–42]

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|1\rangle_\ell|0\rangle_{-\ell} + |0\rangle_\ell|1\rangle_{-\ell}), \quad (5)$$

where the subscripts denote the two OAM modes. For numerical simulation, it is sufficient to restrict the Hilbert space to the two-mode basis, $|0\rangle_\ell|0\rangle_{-\ell}$, $|0\rangle_\ell|1\rangle_{-\ell}$, $|1\rangle_\ell|0\rangle_{-\ell}$, and $|1\rangle_\ell|1\rangle_{-\ell}$, which can be mapped to the two-qubit computational basis $|0\rangle$, $|1\rangle$, $|2\rangle$, and $|3\rangle$, respectively. The choice of basis is justified by the fact that the atomic side modes have negligible excitations ($\bar{n}_{c(d)} \sim 0$) at typical BEC temperatures (~ 20 nK), and the state $|\psi\rangle$ contains only a single photon. The loss of photons from the cavity will lead to occupation of the state $|0\rangle \equiv |0\rangle_\ell|0\rangle_{-\ell}$, with some finite probability. In the computational basis, the single-photon state is given by $|\psi\rangle \equiv (|1\rangle + |2\rangle)/\sqrt{2}$, which indicates the information encoded in a

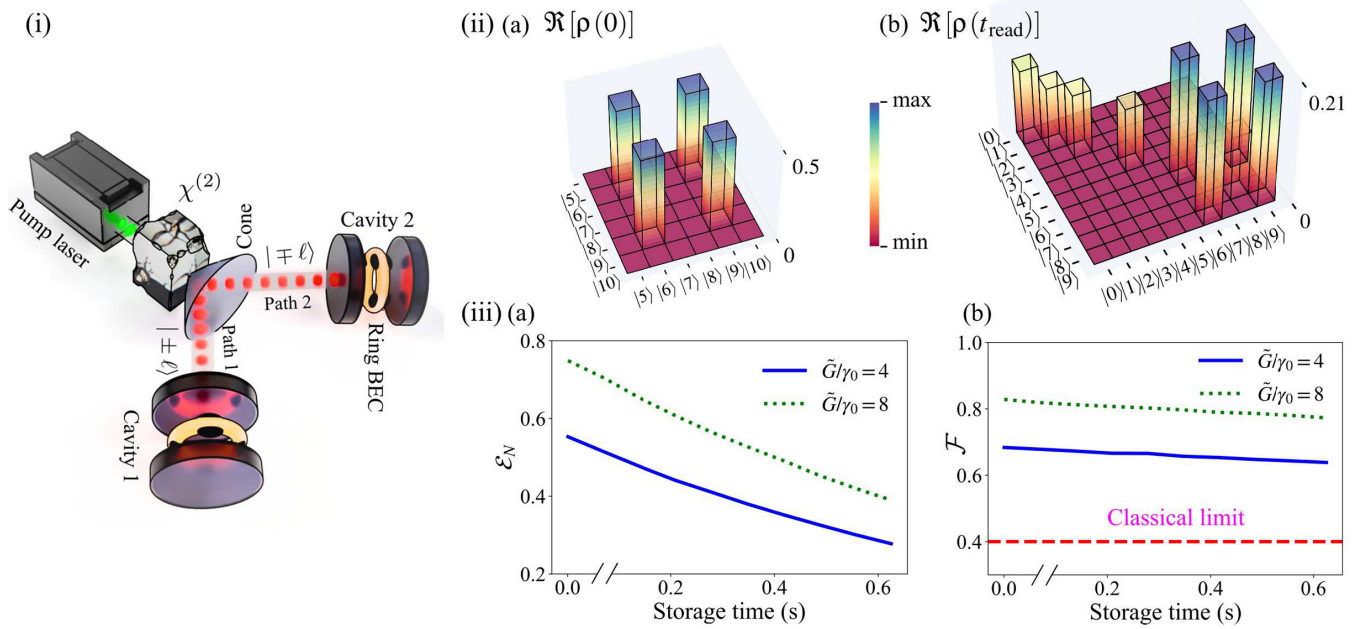


FIG. 3. (i) Schematic showing preparation of OAM-entangled photons and their coupling into cavities 1 and 2. (ii) (a), (b) Initial and retrieved density matrices. (iii) (a) Logarithmic negativity ($\mathcal{E}_N$) vs storage time ($\sim 0.6 \mu\text{s}$ to 0.6 s). (b) Corresponding retrieval fidelity ($\mathcal{F}$) vs storage time for various $\tilde{G}/\gamma_0$. The red dashed line denotes the classical fidelity limit. Parameters for panel (ii) are the same as in Fig. 1.

single qubit [43]. The elements of the initial density matrix $\rho(0)$ and retrieved density matrix $\rho(t_{\text{read}})$ obtained by solving the relevant Lindblad equation are shown in Figs. 2(ii)(a) and 2(ii)(b), respectively. The nonzero probability of finding no photon in either OAM mode, resulting from losses due to imperfect state transfer, can be seen in Fig. 2(ii)(b). The overlap between the initial and retrieved states is quantified by the retrieval fidelity defined as $\mathcal{F} = \text{Tr}[\sqrt{\rho(0)^{1/2}\rho(t_{\text{read}})\rho(0)^{1/2}}]^2$ [44]. The retrieval fidelity as a function of storage time for various $\tilde{G}/\gamma_0$ is presented in Fig. 2(iii). The classical fidelity benchmark is given by $\mathcal{F}_c = (N+1)/(N+2)$ [45–47], where N is the number of qubits. Since $|\psi\rangle$ is a single OAM qubit state ($N=1$), $\mathcal{F}_c = 2/3$, indicated by the red dashed line in Fig. 2(iii). As can be seen from the figure, with an optimized coupling strength of $\tilde{G}/\gamma_0 = 8$, fidelities of $\sim 88\%$ can be achieved for a storage of about $\sim 0.5 \text{ s}$, which exceeds $\mathcal{F}_c$.

C. OAM $\pm\hbar$ entangled state

We now consider the storage of photon pairs entangled in the OAM degree of freedom. These can be produced using spontaneous parametric down-conversion [48], as shown schematically in Fig. 3(i). In the second quantization formalism, the resulting two-photon entangled state can be written as

$$|\psi\rangle_{1,2} = \frac{1}{\sqrt{2}}(|1, 0\rangle_1|0, 1\rangle_2 + |0, 1\rangle_1|1, 0\rangle_2), \quad (6)$$

where, in the notation $|m, n\rangle_i$, $m(n)$ denotes the occupation number of the $|\ell\rangle$ ($|\ell\rangle$) OAM mode in the i th path ($i=1, 2$). This makes $|\psi\rangle_{1,2}$ a four-qubit state. Treating each path as a qubit, the above state can be written in terms of the two-qubit computation basis introduced above as

$|\psi\rangle_{1,2} = (|2\rangle_1|1\rangle_2 + |1\rangle_1|2\rangle_2)/\sqrt{2}$. For compact representation of the density matrix, the four-qubit basis $\{|i, j, k, l\rangle\}$ is mapped to $\{|n\rangle\}$ so that $|i, j, k, l\rangle = |p\rangle_1|q\rangle_2 = |n\rangle$ with $n = 4p + q$ ($p, q = 1, 2, 3$). Here, n is the binary equivalent of the bit string in $\{|i, j, k, l\rangle\}$.

The photons traveling through paths 1 and 2 are stored in two ring BEC-equipped cavities labeled 1 and 2, respectively, in Fig. 3(i) where for pictorial clarity the control fields have been omitted. The retrieved photons from these two cavities are analyzed to verify the preservation of entanglement, following a protocol similar to that of Ref. [49]. The Hamiltonian of the composite system is given by

$$H_{\text{ent}} = \sum_{j=1}^2 H_j(a_{j,\pm\ell}, \tilde{G}_{j,\pm\ell}, c_j, d_j, t), \quad (7)$$

where $H_{1(2)}$ has the exact form as in Eq. (4) with the subscript 1 (2) representing the cavity 1 (2).

The real parts of the initial and retrieved density matrices obtained from solving the relevant Lindblad equation are shown in Figs. 3(ii)(a) and 3(ii)(b), respectively. In Fig. 3(ii)(b), nonzero diagonal elements indicate photon loss and the zeros correspond to states forbidden by the conservation of energy, linear momentum, or OAM. To quantify the entanglement $\mathcal{E}_N$ between the photons in paths 1 and 2, we use logarithmic negativity [50] (defined in the Supplemental Material [32]) as our measure. The entanglement of the state $|\psi\rangle_{1,2}$ is initially unity for the bipartition between subsystems 1 and 2. It is decreased by the storage process, as reflected in the initial values in Fig. 3(iii)(a), where $\mathcal{E}_N$ for the retrieved state is plotted versus storage time for different values of $\tilde{G}/\gamma_0$. For the optimized value of $\tilde{G}/\gamma_0 = 8$, $\mathcal{E}_N$ of up to 0.6 can be stored for as long as 0.2 s, with fidelity as high as 0.8, as shown in Figs. 3(iii)(a) and 3(iii)(b), respectively. The red

dashed line in Fig. 3(iii)(b) indicates the average fidelity for teleporting quantum information of dimension d using classical strategies, given by $\mathcal{F}_c = 2/(d + 1)$ [27], which equals $2/5$ for a two-qubit entangled state.

The fidelities thus far have been presented for optimized parameters. The variation in the fidelities as a function of the mechanical damping rate γ_m has been provided in the Supplementary Material [32] as an example of the effect of nonidealities in parameter space. We see that the fidelities degrade, but not precipitously, for reasonable tolerances of $\sim 10\%$. Nonetheless, we emphasize that winding numbers up to $L_p = 20$ that have been achieved for rotational eigenstates [30] already provide a 40-dimensional Hilbert space, which is significantly larger than any cold atomic ground state trap-pable manifold. Recent developments in coherent control of condensates have reached $L_p \sim 350$ [19] and subsequently $L_p \sim 10^4$ [33]. Finally, rather than relying on a small number of atomic transitions occurring at wavelengths specified by nature, for writing and storage, our proposal uses the optical resonances of a cavity, which are much larger in number than atomic transitions (and can be easily tuned by changing the cavity length), and thus allow significantly more bandwidth for reading, writing, wavelength conversion [51], and OAM transduction [52]. For example, as quantified in the Supplemental Material [32], in a 100 nm range in the visible, there are $\sim 10^4$ equally spaced resonances for a centimeter-long cavity as opposed to ~ 10 atomic transitions.

IV. CONCLUSION

We have proposed a platform for the storage and retrieval of quantum states of light encoded in the OAM basis using a ring BEC-cavity system. For optimized parameters, this platform enables significantly longer storage times (~ 0.3 s)

while achieving retrieval fidelities of $\sim 90\%$ for the OAM superposition state and $\sim 80\%$ for the entangled OAM state, surpassing existing cold-atom-based quantum memory protocols for OAM-encoded qubits, which are typically limited to hundreds of microseconds. Further, our scheme avoids problems associated with EIT protocols and offers a large number of motional states for storage and cavity resonances for reading and writing. Finally, due to the equivalence of the system Hamiltonian with that of standard optomechanical systems, our model naturally supports OAM transduction [52], wavelength conversion [51], and nondestructive readout [29], broadening its potential for integration into quantum information networks.

ACKNOWLEDGMENTS

M.B. thanks the Air Force Office of Scientific Research (AFOSR) (FA9550-23-1-0259) for support. N.D. acknowledges Sarmad Maqsood for assistance with the diagrams and Jhair Gallardo for setting up the computational environment. R.G. acknowledges financial support from CSIR-HRDG, India. P.K. acknowledges the financial support provided by the Max Planck Society. H.S.D. acknowledges funding from SERB/ANRF-DST, India (CRG/2021/008918), and IRCC, IIT Bombay (RD/0521-IRCCSH0-001). We are grateful for stimulating conversations with T. Chakraborty, T.N. Dey, and A. Sen (De). All simulation results in this work were obtained using the open source Python library QuTiP [53].

DATA AVAILABILITY

The codes that support the findings of this article are openly available [54], and include simulation routines and parameters required to reproduce the key results and figures.

-
- [1] K. Heshami, D. G. England, P. C. Humphreys, P. J. Bustard, V. M. Acosta, J. Nunn, and B. J. Sussman, Quantum memories: Emerging applications and recent advances, *J. Mod. Opt.* **63**, 2005 (2016).
 - [2] A. I. Lvovsky, B. C. Sanders, and W. Tittel, Optical quantum memory, *Nat. Photonics* **3**, 706 (2009).
 - [3] L. Veissier, Quantum memory protocols in large cold atomic ensembles, Theses, Université Pierre et Marie Curie—Paris VI, 2013.
 - [4] C. He, Y. Shen, and A. Forbes, Towards higher-dimensional structured light, *Light Sci. Appl.* **11**, 205 (2022).
 - [5] B.-S. Shi, D.-S. Ding, and W. Zhang, Quantum storage of orbital angular momentum entanglement in cold atomic ensembles, *J. Phys. B: At. Mol. Opt. Phys.* **51**, 032004 (2018).
 - [6] D.-S. Ding, W. Zhang, S. Shi, Z.-Y. Zhou, Y. Li, B.-S. Shi, and G.-C. Guo, High-dimensional entanglement between distant atomic-ensemble memories, *Light Sci. Appl.* **5**, e16157 (2016).
 - [7] D.-S. Ding, W. Zhang, Z.-Y. Zhou, S. Shi, G.-Y. Xiang, X.-S. Wang, Y.-K. Jiang, B.-S. Shi, and G.-C. Guo, Quantum storage of orbital angular momentum entanglement in an atomic ensemble, *Phys. Rev. Lett.* **114**, 050502 (2015).
 - [8] A. Nicolas, L. Veissier, L. Giner, E. Giacobino, D. Maxein, and J. Laurat, A quantum memory for orbital angular momentum photonic qubits, *Nat. Photonics* **8**, 234 (2014).
 - [9] D. Moretti, D. Felinto, and J. W. R. Tabosa, Collapses and revivals of stored orbital angular momentum of light in a cold-atom ensemble, *Phys. Rev. A* **79**, 023825 (2009).
 - [10] L. Veissier, A. Nicolas, L. Giner, D. Maxein, A. S. Sheremet, E. Giacobino, and J. Laurat, Reversible optical memory for twisted photons, *Opt. Lett.* **38**, 712 (2013).
 - [11] C. Wang, Y. Yu, Y. Chen, M. Cao, J. Wang, X. Yang, S. Qiu, D. Wei, H. Gao, and F. Li, Efficient quantum memory of orbital angular momentum qubits in cold atoms, *Quantum Sci. Technol.* **6**, 045008 (2021).
 - [12] Z.-Q. Zhou, Y.-L. Hua, X. Liu, G. Chen, J.-S. Xu, Y.-J. Han, C.-F. Li, and G.-C. Guo, Quantum storage of three-dimensional orbital-angular-momentum entanglement in a crystal, *Phys. Rev. Lett.* **115**, 070502 (2015).
 - [13] Y.-H. Ye, L. Zeng, M.-X. Dong, W.-H. Zhang, E.-Z. Li, D.-C. Li, G.-C. Guo, D.-S. Ding, and B.-S. Shi, Long-lived memory for orbital angular momentum quantum states, *Phys. Rev. Lett.* **129**, 193601 (2022).

- [14] A. J. Leggett, Bose-Einstein condensation in the alkali gases: Some fundamental concepts, *Rev. Mod. Phys.* **73**, 307 (2001).
- [15] O. Morizot, Y. Colombe, V. Lorent, H. Perrin, and B. M. Garraway, Ring trap for ultracold atoms, *Phys. Rev. A* **74**, 023617 (2006).
- [16] B. E. Sherlock, M. Gildemeister, E. Owen, E. Nugent, and C. J. Foot, Time-averaged adiabatic ring potential for ultracold atoms, *Phys. Rev. A* **83**, 043408 (2011).
- [17] C. Ryu, M. F. Andersen, P. Cladé, V. Natarajan, K. Helmerson, and W. D. Phillips, Observation of persistent flow of a Bose-Einstein condensate in a toroidal trap, *Phys. Rev. Lett.* **99**, 260401 (2007).
- [18] K. C. Wright, R. B. Blakestad, C. J. Lobb, W. D. Phillips, and G. K. Campbell, Driving phase slips in a superfluid atom circuit with a rotating weak link, *Phys. Rev. Lett.* **110**, 025302 (2013).
- [19] Y. Guo, R. Dubessy, M. de Goër de Herve, A. Kumar, T. Badr, A. Perrin, L. Longchambon, and H. Perrin, Supersonic rotation of a superfluid: A long-lived dynamical ring, *Phys. Rev. Lett.* **124**, 025301 (2020).
- [20] J. Polo, W. J. Chetcuti, T. Haug, A. Minguzzi, K. Wright, and L. Amico, Persistent currents in ultracold gases, *Phys. Rep.* **1137**, 1 (2025).
- [21] A. Ramanathan, K. C. Wright, S. R. Muniz, M. Zelan, W. T. Hill, C. J. Lobb, K. Helmerson, W. D. Phillips, and G. K. Campbell, Superflow in a toroidal Bose-Einstein condensate: An atom circuit with a tunable weak link, *Phys. Rev. Lett.* **106**, 130401 (2011).
- [22] S. Beattie, S. Moulder, R. J. Fletcher, and Z. Hadzibabic, Persistent currents in spinor condensates, *Phys. Rev. Lett.* **110**, 025301 (2013).
- [23] K. T. Kapale and J. P. Dowling, Vortex phase qubit: Generating arbitrary, counterrotating, coherent superpositions in Bose-Einstein condensates via optical angular momentum beams, *Phys. Rev. Lett.* **95**, 173601 (2005).
- [24] M. Lettner, M. Mücke, S. Riedl, C. Vo, C. Hahn, S. Baur, J. Bochmann, S. Ritter, S. Dürr, and G. Rempe, Remote entanglement between a single atom and a Bose-Einstein condensate, *Phys. Rev. Lett.* **106**, 210503 (2011).
- [25] K. Hammerer, A. S. Sørensen, and E. S. Polzik, Quantum interface between light and atomic ensembles, *Rev. Mod. Phys.* **82**, 1041 (2010).
- [26] J. Leach, M. J. Padgett, S. M. Barnett, S. Franke-Arnold, and J. Courtial, Measuring the orbital angular momentum of a single photon, *Phys. Rev. Lett.* **88**, 257901 (2002).
- [27] M. Horodecki, P. Horodecki, and R. Horodecki, General teleportation channel, singlet fraction, and quasidistillation, *Phys. Rev. A* **60**, 1888 (1999).
- [28] A. M. Yao and M. J. Padgett, Orbital angular momentum: Origins, behavior and applications, *Adv. Opt. Photonics* **3**, 161 (2011).
- [29] P. Kumar, T. Biswas, K. Feliz, R. Kanamoto, M.-S. Chang, A. K. Jha, and M. Bhattacharya, Cavity optomechanical sensing and manipulation of an atomic persistent current, *Phys. Rev. Lett.* **127**, 113601 (2021).
- [30] S. Simjanovski, G. Gauthier, M. J. Davis, H. Rubinsztein-Dunlop, and T. W. Neely, Optimizing persistent currents in a ring-shaped Bose-Einstein condensate using machine learning, *Phys. Rev. A* **108**, 063306 (2023).
- [31] A. D. Ludlow, X. Huang, M. Notcutt, T. Zanon-Willette, S. M. Foreman, M. M. Boyd, S. Blatt, and J. Ye, Compact, thermal-noise-limited optical cavity for diode laser stabilization at 1×10^{-15} , *Opt. Lett.* **32**, 641 (2007).
- [32] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/zd1d-39d7> for the detailed derivation of the Hamiltonian, a protocol for generating single photons in $\pm \ell \hbar$ OAM coherent superpositions, fidelity analysis with logarithmic negativity entanglement quantification, the variation of storage time with mechanical damping, and a discussion of cavity resonances, which includes Refs. [28,30,31,34,37,40].
- [33] S. Pandey, H. Mas, G. Drougakis, P. Thekkeppatt, V. Bolpasi, G. Vasilakis, K. Poullos, and W. von Klitzing, Hypersonic Bose-Einstein condensates in accelerator rings, *Nature (London)* **570**, 205 (2019).
- [34] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, Cavity optomechanics, *Rev. Mod. Phys.* **86**, 1391 (2014).
- [35] V. Fiore, Y. Yang, M. C. Kuzyk, R. Barbour, L. Tian, and H. Wang, Storing optical information as a mechanical excitation in a silica optomechanical resonator, *Phys. Rev. Lett.* **107**, 133601 (2011).
- [36] S. Weis, R. Rivière, S. Deléglise, E. Gavartin, O. Arcizet, A. Schliesser, and T. J. Kippenberg, Optomechanically induced transparency, *Science* **330**, 1520 (2010).
- [37] S. Kalita, P. Kumar, R. Kanamoto, M. Bhattacharya, and A. K. Sarma, Pump-probe cavity optomechanics with a rotating atomic superfluid in a ring, *Phys. Rev. A* **107**, 013525 (2023).
- [38] C. Gardiner and P. Zoller, Quantum markov processes, in *Quantum Noise* (Springer, Berlin Heidelberg, 2004).
- [39] E. J. Galvez, L. E. Coyle, E. Johnson, and B. J. Reschovsky, Interferometric measurement of the helical mode of a single photon, *New J. Phys.* **13**, 053017 (2011).
- [40] C. Gerry and P. Knight, Beam splitters and interferometers, in *Introductory Quantum Optics* (Cambridge University Press, Cambridge, 2004), pp. 135–149.
- [41] E. Lombardi, F. Sciarrino, S. Popescu, and F. De Martini, Teleportation of a vacuum-one-photon qubit, *Phys. Rev. Lett.* **88**, 070402 (2002).
- [42] H.-W. Lee and J. Kim, Quantum teleportation and bell's inequality using single-particle entanglement, *Phys. Rev. A* **63**, 012305 (2000).
- [43] E. Knill, R. Laflamme, and G. J. Milburn, A scheme for efficient quantum computation with linear optics, *Nature (London)* **409**, 46 (2001).
- [44] S. Huang, Quantum state transfer in cavity electro-optic modulators, *Phys. Rev. A* **92**, 043845 (2015).
- [45] S. Massar and S. Popescu, Optimal extraction of information from finite quantum ensembles, *Phys. Rev. Lett.* **74**, 1259 (1995).
- [46] K. Hammerer, M. M. Wolf, E. S. Polzik, and J. I. Cirac, Quantum benchmark for storage and transmission of coherent states, *Phys. Rev. Lett.* **94**, 150503 (2005).
- [47] M. Gündoğan, P. M. Ledingham, A. Almasi, M. Cristiani, and H. de Riedmatten, Quantum storage of a photonic polarization qubit in a solid, *Phys. Rev. Lett.* **108**, 190504 (2012).
- [48] R. Fickler, R. Lapkiewicz, W. N. Plick, M. Krenn, C. Schaeff, S. Ramelow, and A. Zeilinger, Quantum entanglement of high angular momenta, *Science* **338**, 640 (2012).
- [49] S. Kiesewetter, R. Teh, P. Drummond, and M. Reid, Pulsed entanglement of two optomechanical oscillators and furry's hypothesis, *Phys. Rev. Lett.* **119**, 023601 (2017).

- [50] R. Ghobadi, A. R. Bahrapour, and C. Simon, Quantum optomechanics in the bistable regime, *Phys. Rev. A* **84**, 033846 (2011).
- [51] L. Tian and H. Wang, Optical wavelength conversion of quantum states with optomechanics, *Phys. Rev. A* **82**, 053806 (2010).
- [52] H. Kaviani, R. Ghobadi, B. Behera, M. Wu, A. Hryciw, S. Vo, D. Fattal, and P. Barclay, Optomechanical detection of light with orbital angular momentum, *Opt. Express* **28**, 15482 (2020).
- [53] J. Johansson, P. Nation, and F. Nori, QuTiP: An open-source python framework for the dynamics of open quantum systems, *Comput. Phys. Commun.* **183**, 1760 (2012).
- [54] N. Daloi, R. Gupta, A. Ghosh, P. Kumar, H. S. Dhar, and M. Bhattacharya, Ring_BEC_Quantum_Memory, 2025, https://github.com/qid-iitb/Ring_BEC_Quantum_Memory.