

Light-induced fictitious magnetic fields for quantum storage in cold atomic ensembles

Jianmin Wang^{1,2,3,*}, Liang Dong^{1,4,*}, Xingchang Wang^{1,2}, Zihan Zhou^{1,2}, Jinshuai Huang^{1,4}

Ying Zuo^{1,2,†}, Georgios A. Siviloglou^{1,2,5,‡} and J. F. Chen^{1,2,4,§}

¹Shenzhen Institute for Quantum Science and Engineering *Southern University of Science and Technology*, Shenzhen 518055, China

²International Quantum Academy, Shenzhen 518048, China

³Department of Physics, City *University of Hong Kong*, Kowloon, Hong Kong SAR, China

⁴Department of Physics, *Southern University of Science and Technology*, Shenzhen 518055, China

⁵Department of Physics, *University of Crete*, 71003 Heraklion, Greece



(Received 14 June 2024; accepted 4 September 2024; published 2 October 2024)

In this paper, we have demonstrated that optically generated fictitious magnetic fields can be utilized to extend the lifetime of quantum memories in cold atomic ensembles. All the degrees of freedom of an AC Stark shift, such as polarization, spatial profile, and temporal waveform, can be readily controlled in a precise manner. Temporal fluctuations over several experimental cycles and spatial inhomogeneities along a cold atomic gas have been compensated by an optical beam. The advantage of employing fictitious magnetic fields for quantum storage lies in the speed and spatial precision with which these fields can be synthesized. Our simple and versatile technique can find widespread application in coherent pulse and single-photon storage across various atomic species.

DOI: [10.1103/PhysRevResearch.6.L042002](https://doi.org/10.1103/PhysRevResearch.6.L042002)

Introduction. Storing and retrieving information in network nodes are crucial building elements for diverse applications ranging from long-distance quantum communication [1,2] to large-scale quantum computation and simulation [3]. Quantum storage of single photons as well as memories for coherent light have been realized in a plethora of physical systems ranging from single atoms in optical cavities [4], to hot atomic vapors [5] and Mott insulators of quantum degenerate gases [6], and from ion-doped crystals [7] to optical microresonators [8]. Cold atomic ensembles, in particular, can be ideal memory platform not only for leading to the highest efficiency storage in record [9,10] but also enabling storage of diverse types of quantum states [11–14].

In recent years, while considerable progress has been made for the storage efficiency of absorptive quantum memories [2,15,16] based on elongated cold atomic ensembles [9–11,17], a critical challenge still persists: extending storage lifetimes. Up to now, quantum qubits or photonic entangled states with that exhibit storage efficiencies higher than 80% suffer from short storage lifetimes, typically below 100 μ s, that is the threshold for quantum communication within metropolitan areas [2,11,17].

Several mechanisms lead to the degradation of stored quantum states in an atomic ensemble over time. The influence of the Doppler broadening and motional dephasing of the stored spin waves can be reduced by increasing the wavelength of

the spin waves via perfect phase matching between optical fields [18], cooling the atomic gases to sub-Doppler temperatures [19], and further limiting the atomic motion by the means of optical lattices [20]. However, even with minimized atomic motion atomic ensembles still suffer from decoherence caused by ambient magnetic fields, and therefore magnetically insensitive clock transitions, e.g., $(m_F, m_{F'}) = (0,0)$ can be chosen [21]. Together with dynamical decoupling, which is efficient for dephasing because of inhomogeneous broadening, the storage lifetime can be extended to seconds, but the above operations generally result in lower atom numbers, and thus retrieval efficiencies in the order of 10% [22,23].

To achieve both appreciable storage efficiency and lifetime, precise control of the residual magnetic fields on the atomic ensemble is essential. The deleterious effects of the external magnetic fields are typically addressed by the active stabilization from compensation current-carrying coils [24–26]. However, to reach high optical densities and therefore sufficient storage efficiency, the atomic clouds must be more than 2 cm in length, and the spatial gradient of magnetic field caused by the compensation coils is then detrimental. Meter-scale compensations coils generate relatively smooth fields and therefore cannot compensate for inhomogeneities in the scale of millimeters. In addition, they are typically rather slow with activation times in the order of several milliseconds. Therefore, compensating for these spatial inhomogeneities in such timescales could benefit from a complementary experimental approach. One promising path to address these challenges involves exploiting the AC Stark effect [27]. The AC Stark effect was originally introduced to describe the energy shifts on an atomic level induced by time-varying electric fields, and it is caused by the tendency of the atomic dipoles to align with these light-induced oscillating electric fields [28,29]. As was demonstrated recently, AC Stark shifts of spatially imperfect optical beams can have a direct influence on free-induction decay signal (FID) [30]. AC Stark shifts

*These authors contributed equally to this work.

†Contact author: zuoying@iqasz.cn

‡Contact author: siviloglouga@sustech.edu.cn

§Contact author: chenjf@sustech.edu.cn

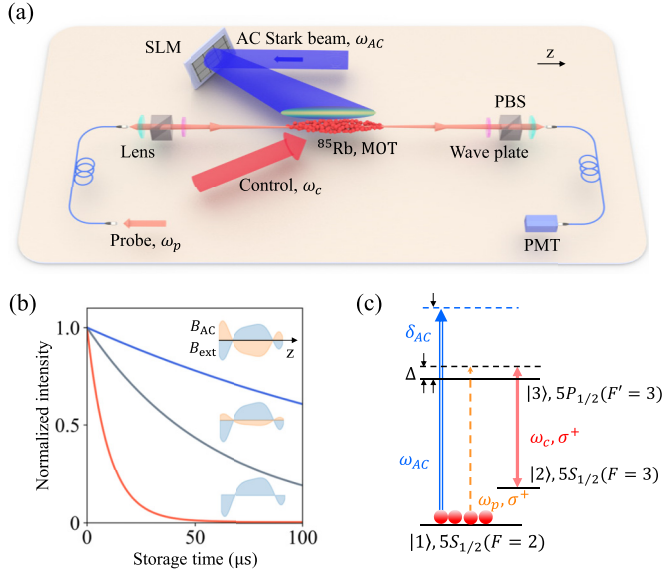


FIG. 1. Experimental scheme for controlling atomic optical storage with fictitious magnetic fields. (a) Optical setup. A pulsed probe signal, ω_p , is stored via EIT by a control beam, ω_c , in an elongated atomic cloud. The retrieved signal, ω_p , is detected after storage by a high-gain photomultiplier (PMT). An AC Stark shift laser beam, ω_{AC} , is utilized to compensate for inhomogeneities that lead to storage decay. (b) Mechanism of compensation of nonuniform energy shifts by fictitious magnetic fields. When $B_{AC}(z) = -B_{ext}(z)$ the maximum storage is reached. (c) Λ configuration for atomic optical storage and the AC Stark laser beam. The atoms are initially prepared in the ground state $|1\rangle$. The probe and the control beams are both circularly polarized. All these laser beams have a wavelength of approximately 795 nm.

have emerged as a powerful tool in fundamental science and in quantum technology research with widespread application in atomic spectroscopy, laser cooling and trapping, spin wave manipulation [30–32], and even in single-spin addressing [33], among many others.

In this Letter, we demonstrate the efficacy of precisely controlled fictitious magnetic fields, generated by AC Stark shifts [27], for extending the lifetime of quantum memories in cold atomic ensembles. Our approach harnesses the full flexibility of AC Stark shift beams (alternatively AC beams), allowing precise engineering of polarization, spatial profile, and temporal waveform to compensate for temporal fluctuations and spatial inhomogeneities of magnetic origin in an atomic ensemble. We demonstrate experimentally that the vector components of the AC Stark shifts can act on quantum storage equivalently to standard magnetic fields. Notably, with high speed and spatial precision, the fictitious magnetic field generated via nondestructive configurable AC Stark potentials offers a versatile method to manipulate atomic coherence in diverse physical systems such as atoms and ion-doped solids across various settings such as processors based on spin waves, gradient echo configurations, and even atomic clocks and quantum simulators.

Experimental setup and theory. We use an elongated cloud of cooled rubidium atoms to perform optical storage, as shown in Fig. 1(a). The atoms are prepared to the lowest hyperfine manifold $|1\rangle$ in a dark-line two-dimensional magneto-optical

trap (MOT) [34]. After MOT loading, the atoms are released, and a 1.7 ms experimental window of light storage and retrieval starts. A submicrowatt pulse of laser light ω_p is stored as atomic coherence by a control beam ω_c utilizing an electromagnetically induced transparency (EIT) storage scheme when $\Delta = 0$ [35] or a Raman scheme for $\Delta \neq 0$ [36]. An AC Stark shift beam ω_{AC} is spatially engineered to have a highly controllable intensity or polarization profile by a spatial light modulator [37,38], while its temporal waveform can also be synthesized by arbitrary signal generators. In general, the complex Rabi frequency of this AC Stark shift beam, which is used to compensate for unwanted Zeeman shifts and thus extend the lifetime of the stored atomic coherence, can take the spatiotemporally modulated form of $\Omega_{AC}(x, y, z, t)$. In Fig. 1(b), we elucidate the physical mechanism that enables us to rectify spatial inhomogeneities (or temporal fluctuations if $z \rightarrow t$) of the spin wave distribution. The three-level system for light storage in ^{85}Rb together with the AC Stark beam is shown in Fig. 1(c) [39].

In general, the Hamiltonian of a multilevel atomic gas interacting with a laser beam will have spin-dependent terms. The energy shifts of the various m_F states can be classified as scalar, vector, and tensor, and the spin-dependent vector shifts are the ones utilized here for controlling the storage lifetimes [40]. A single beam with nonuniform spatial profile and arbitrary polarization can generate a space-dependent synthetic magnetic field. The situation is quite simpler for an AC Stark shift beam interacting with ^{85}Rb atoms with a detuning δ_{AC} larger than the hyperfine splitting ($\Delta E_{\text{hfs}} = 3.036 \text{ GHz}$), and at the same time much smaller than the fine structure splitting ($\Delta E_{fs} = 7.1 \text{ THz}$) [39]. The contribution of the tensor term is negligible, while the scalar term causes m_F -independent shifts, which are at the same time much smaller than the spectral window of the EIT, so they can be ignored for space-independent fictitious fields (see the Supplemental Material [41]). In this case, the experimentally relevant part of the Hamiltonian H will be approximated only by a spin-dependent, Zeeman-like vector term H_v that for a given detuning δ_{AC} is proportional to the intensity of the AC beam, as well as the involved m_F state (see the Supplemental Material [41]). This vector term takes the simple form

$$H_v(x, y, z, t) = q\mu_{AC}m_F|\Omega_{AC}(x, y, z, t)|^2, \quad (1)$$

where $q = 0, \pm 1$ represents respectively linearly and circularly polarized AC light, μ_{AC} depends on the associated atomic transitions and can be considered an effective Bohr magneton-like factor that converts fictitious magnetic fields to energy shifts. This fictitious magnetic field term H_v can in principle be spatiotemporally modulated following the Rabi frequency Ω_{AC} [30].

Equation (2) provides a direct way to elucidate the physical mechanism that relates magnetic fields and the time dependence of quantum storage retrieval efficiency η [20,41–44],

$$\eta(t) = |\langle \Psi_t | \Psi_{t=0} \rangle|^2 = \left| \frac{1}{N} \sum_{m_F, m_{F'}} a_{m_F} \int n(z) e^{i\mu_B g_{FF'}(m_F, m_{F'})(B_0 + B_1 z + B_2 z^2)t} dz \right|^2 \times \exp(-\Gamma t). \quad (2)$$

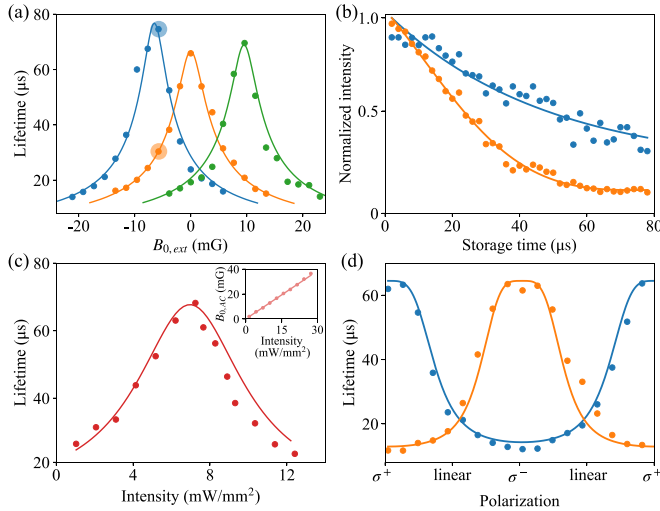


FIG. 2. Controlling optical storage in an atomic ensemble with an AC Stark beam. (a) Storage lifetime as a function of compensation coil magnetic field along the direction z . The three curves correspond to AC Stark shifts equivalent to 6.7 mG (blue), 0 mG (orange), and -9.6 mG (green). (b) The orange curve illustrates the relationship between storage efficiency and storage time at a residual magnetic field of 5.8 mG. The blue curve represents the result compensated by fictitious magnetic field. These curves correspond the shadowed discs of (a). (c) Storage lifetime as a function of the AC Stark beam intensity. The inset shows the linear dependence of the fictitious magnetic field on the intensity of an AC Stark beam. (d) Storage lifetime as function of the polarization of the AC Stark shift beam for two different initial external magnetic fields 9.6 mG (orange) and -7.7 mG (blue). The reported fields are the ones experimentally determined, while the fitting curves (see the Supplemental Material [41]) correspond to theoretical fields scaled by 0.5.

In Eq. (2), for notation simplicity, we do not differentiate the standard from the light-induced magnetic fields. $n(z)$ is the spatial distribution of the cold atomic ensemble with the total atoms number of N . a_{m_F} are the factors associated with the population of the m_F states and the strength of the relevant two-photon transitions for storage. $g_{FF'} = m_{F'}g_{F'} - m_Fg_F$, where g_F and $g_{F'}$ are the g factor of the corresponding atomic levels. For same polarization q for the probe and control beams of the storage scheme $m_{F'} = m_F + q$. The magnetic field terms $B_{0,1,2}$ refer to bias, gradient, and curvature, respectively. The exponential decay factor can also be replaced by a Gaussian one depending on the origin of any additional decoherence mechanisms that do not stem from magnetic fields, such as motional dephasing [18].

Controlling storage by AC Stark shifts. Storage of light in a cold atomic ensemble is particularly sensitive to spin-dependent energy shifts that commonly originate from uncompensated magnetic fields [42]. In Fig. 2, we experimentally demonstrate how an AC Stark beam that emulates synthetic magnetic fields can optically control the storage in an atomic memory. Here, to create a spatially uniform fictitious magnetic field along the long axis of the MOT we use an AC beam with a waist radius of 1 mm propagating practically parallel to this axis ($\theta = 3^\circ$) with a detuning $\delta_{AC} = 2\pi \times 25.6$ GHz.

In Fig. 2(a), we show that the energy shifts because of the AC beams create effective bias magnetic fields that with respect to storage lifetimes are indistinguishable from fields generated from standard magnetic coils [27]. To demonstrate this, the current in a compensation coil along the direction z is varied when no AC beam is present or when an AC beam, with an intensity of $I_{AC} = 4.5$ mW/mm² and circular polarization σ^+ or σ^- is applied. The reversal of polarization, as indicated in Eq. (1), leads to opposite magnetic fields, while the distance of the peaks is a direct measure of the magnetic field amplitudes [27].

Two typical storage decay curves are presented in Fig. 2(b). When the residual bias magnetic field along the MOT axis is uncompensated a shorter lifetime is observed [42], when the AC Stark beam creates a bias-like energy shift the storage is restored. The AC-induced field is experimentally estimated to be 5.8 mG and has a direction along z . We attribute a nominal field zero for the maximum lifetime achieved only by bias compensation.

We illustrate the effect of the AC Stark beam optical power to the light storage in Fig. 2(c). Each data point is retrieved from the $1/e$ decay of curves similar to Fig. 2(b), while the fitting curves are calculated based on Eq. (2). A slight asymmetry on the high-power side can be attributed to optical pumping and scattering because of the AC beam (see the Supplemental Material [41]). Our assumption is that these effects pose the main limits on the maximum effective magnetic fields reachable. Figure 2(c) (inset) shows the expected linear dependence of the AC-induced magnetic fields on the optical intensity.

The polarization of an AC Stark shift can provide an additional degree of freedom and can be used to generate arbitrary magnetic fields [27]. In Fig. 2(d), the storage lifetime is measured when the polarization is tuned continuously from left to right circular passing from the zero-magnetic fields linear case.

Space-dependent fictitious magnetic fields. Precise manipulation of fictitious magnetic fields in the spatial domain can be instrumental in correcting for inhomogeneities that stem from nonuniform stray magnetic fields. Recent experiments on quantum storage of photons in cold atomic ensembles have attributed certain limitations to the storage lifetimes to inhomogeneities in the range of $\Delta B = 10$ mG [9,45]. In Fig. 3, we demonstrate that AC Stark shifts can introduce effective magnetic fields that match the most commonly occurring lowest-order inhomogeneities such as linear and quadratic. We have utilized a Raman storage scheme [36,46] that addresses only one of the available ground magnetic states m_F , and therefore the contributions of the bias fields are decoupled from the storage lifetimes. Spatial modulation of the AC Stark shift beam has been done by a spatial light modulator (SLM) [37,38] as shown in Fig. 1(a) and detailed within the Supplemental Material [41].

As shown in Fig. 3(a), with double axes we demonstrate the similar dependence of storage on magnetic field gradients on a current coil and the AC Stark beam. The fitting curve for the AC-Stark results (blue line) is based on Eq. (2), for gradients with a maximum value of 9 mG/cm and 2 mG/cm for polarizations σ^- and σ^+ respectively, with optical power $P = 17.4$ mW for a red detuning of 17.2 GHz. Figure 3(b)

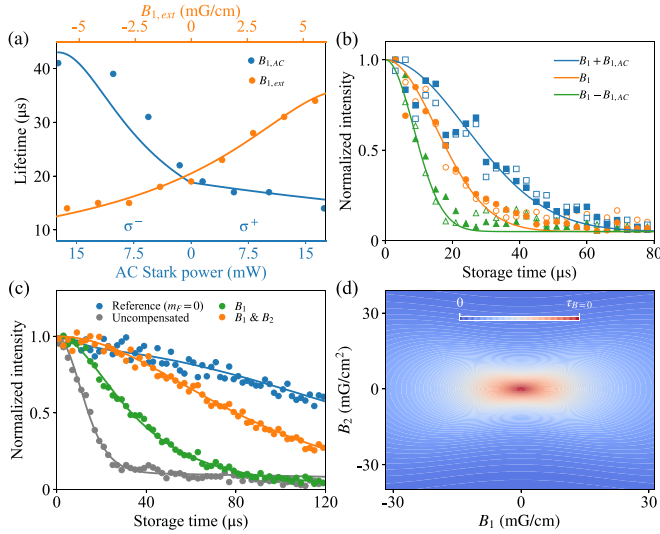


FIG. 3. Compensating spatial inhomogeneities with AC Stark beams. (a) Storage lifetime dependence on the gradient of linearly dependent effective magnetic fields (blue line) induced by an AC Stark beam for σ^+ / σ^- polarizations, and standard magnetic fields with opposite gradient $B_{1,ext}$ (orange line). The lifetimes are the $1/e$ points for curves similar to (b). (b) Retrieved pulse intensities as a function of time for optically induced gradient $\pm B_{1,AC}$ (green/blue open markers), and standard magnetic field gradient $\pm B_{1,ext}$ (green/blue solid markers). The orange curve and data correspond to the storage decay when no compensation is applied (orange open markers) and when the two fields opposite to each other (orange-solid markers). (c) Storage lifetime dependence for the state $m_F = 1$ when no compensation fictitious magnetic fields are applied ($B_{AC} = 0$, gray line), when a gradient field partially compensates the nonuniformities because of a quantization field ($B_{AC} = +B_{1,AC}z$, green line), and when a quadratic term is also added ($B_{AC} = B_{1,ext}z + B_{2,AC}z^2$, orange line). The reference (blue line) is the storage decay starting from the nonmagnetic $m_F = 0$ state. (d) Theoretical prediction of the storage lifetimes as a function of uncompensated linear B_1 and quadratic terms B_2 for the $m_F = 1$ state. The colormap is normalized to a maximum storage time $\tau_{B=0}$ that is independent of magnetic fields.

shows that optically induced AC Stark shifts with linear space dependence can correct for the weak residual gradient magnetic fields existing in the environment. This residual field leads to a storage lifetime of approximately $22 \mu\text{s}$ (orange line) for the state $m_F = 1$. When the AC Stark beam with linear dependence and positive slope, because of the polarization σ^- , is applied, $+B_{1,AC}z$, the lifetime can be improved (blue line). On the other hand, if the polarization is reversed the effective field gradient will be opposite, $-B_{1,AC}z$, and the storage will be severely reduced (green line). We have also demonstrated that an AC-induced gradient (solid markers) can have identical effect with a purely current-induced magnetic gradient (open markers) and cancel external magnetic field gradients in the order of several mG/cm.

The highest degree of cancellation of magnetic fields would lead to the stored light in magnetic states reaching the magnetically insensitive state $m_F = 0$ that acts as a reference (blue line). With that target, we have compensated the linear gradient (green line), and we have added a

parabolically modulated AC Stark beam $B_{2,AC}z^2$ (orange line) and further improvement of storage lifetime of the completely uncompensated decay (gray line) as shown in Fig. 3(c). By this approach, we have achieved more than a fivefold improvement of the storage lifetime: from $18 \mu\text{s}$ (gray line) to $100 \mu\text{s}$ (orange line). The remaining gap between the highest lifetime of the $m_F = 1$ states and the lifetime of the $m_F = 0$ states can be attributed to higher terms of the uncompensated magnetic fields and contributions from the stray RF fields. The lifetime of the reference state itself is currently predominantly limited by dephasing stemming from thermal motion [18,41]. In Fig. 3(d), we complement our experimental observations with theoretical predictions for the combined effect of linear B_1 and quadratic terms B_2 on the lifetime of light storage in a cold atomic ensemble of $m_F = 1$ atoms [43,44].

Time-dependent fictitious magnetic fields. While compensation of stray magnetic fields is routinely performed with standard current carrying coils, AC Stark shifts because of their optical origin have two distinct features that make them compelling for application in quantum storage: they can be spatially sculpted in the micrometer scale in arbitrary patterns, and in the temporal domain can be readily modulated even in the nanosecond regime. A proof-of-concept demonstration of temporal compensation of external magnetic fields is presented in Fig. 4. Magnetic field variations can be detrimental for an atomic memory and significantly reduce the quality of photon storage via minuscule random fluctuations during the storage time or via larger longer-term instabilities. Here, in Fig. 4, we demonstrate a method to address the longer-term instability issue by compensating a random external magnetic field by employing an AC beam that induces an opposite effective magnetic field. The left panel of Fig. 4(a) shows the time series of the two opposing fields, while its right panel shows a histogram of the $N = 13$ intensity levels of the AC Stark beam (blue line) applied to compensate for the corresponding magnetic fields (red line). The random, Fig. 4(a), but known control magnetic field that can be varied in every experimental cycle is applied to the atoms and the atomic storage decay is observed. As seen in Fig. 4(b), a reduced storage lifetime is observed when no compensation beams are used (orange line). We observed a similar behavior when a calibrated AC beam was applied in isolation. When the control magnetic field and the AC beam are applied together the storage lifetime is restored (blue line) to the no-magnetic-field case (green line).

To demonstrate the robustness of this technique, we have repeated, as shown in Fig. 4(c), this experiment for different peak-to-peak random modulations of the magnetic field and were able to compensate them and restore the storage lifetime to its initial value of approximately $65 \mu\text{s}$ (blue line). The storage lifetimes without AC compensation naturally follow an exponential-like decay (orange line). This decay is in agreement with numerical simulations that average the storage decays for fluctuating magnetic fields with increasing peak-to-peak variations, but with a scaling factor of approximately 0.5.

Conclusions. In this paper, we have demonstrated that optically generated fictitious magnetic fields can extend the lifetime of quantum memories in cold atomic ensembles. All the degrees of freedom of an AC Stark beam, such as polarization, spatial profile, and temporal waveform, can be readily controlled in a precise manner, and remarkable improvements

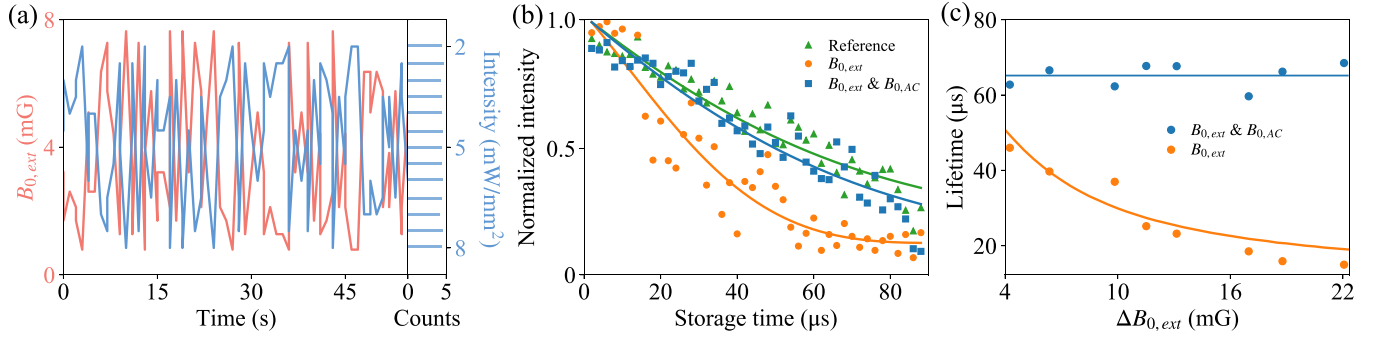


FIG. 4. Controlling optical storage in an atomic ensemble with a time-varying AC Stark beam. (a) (Left) Time series of the random bias magnetic field (red line) changing in 1 Hz, and the corresponding compensating fictitious field (blue line). (Right) a histogram of the uniform intensity distribution of the $N = 13$ values of the AC Stark beam. (b) Retrieved pulse intensity as a function of storage time when only a time-varying control magnetic field in a range of $\Delta B_{0,ext} = 6.8$ mG (orange circles) is applied, when a compensating AC beam is applied simultaneously with the external magnetic field (blue squares), and when no perturbing magnetic or optical fields are applied (green triangles). The solid lines represent the corresponding theoretical fits. (c) Storage lifetimes as a function of time-varied applied magnetic fields in the range $\langle \Delta B_{0,ext} \rangle$ are acting solely (orange circles), and for the case that the AC beam is compensating the field variations (blue circles). The solid lines are a constant (blue line) and a fit from statistical averaging of the fluctuating magnetic fields (orange line).

of the storage lifetime are recorded. AC Stark shift beams have the potential to create synthetic magnetic fields with submicrometer spatial resolution and tens of nanoseconds switching times. The aforementioned advantages of fictitious magnetic fields are particularly pronounced for effective magnetic fields up to a few tens of mG and can be readily used to address inhomogeneities corresponding even down to μ G. A limitation of the demonstrated method is that inhomogeneities of the scalar terms of the AC Stark shifts themselves cannot be simultaneously compensated for all m_F states. An immediate next step is to demonstrate inhomogeneity compensation in the spatiotemporal domain by machine learning [47]. While here we focus on perturbations from magnetic fields our method can find application in other disturbances originating for instance from imperfect profiles of the write and read beams. The versatility of the AC-induced fictitious fields can

complement standard magnetic fields for any storage scheme for other atomic systems, and we envision that can be exploited for realizing periodic artificial gauge fields to manipulate dark state polaritons that are featuring a hybrid atom-photon wavefunction [48,49]. Space dependence can be used to engineer the momentum of the stored spin waves, and the temporal periodicity leads to Floquet engineered effective Hamiltonians similar to the ones emerging for photons [50] and quantum degenerate gases [51].

Acknowledgments. This work is supported by the National Natural Science Foundation of China (NSFC) through Grants No. 12074171, No. 12074168, No. 92265109, No. 12204227 and No. 12474262; the Guangdong projects under Grants No. 2022B1515020096 and No. 2019ZT08X324. X.W. acknowledges the support from the SUSTech Presidential Postdoctoral Fellowship.

- [1] L.-M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, Long-distance quantum communication with atomic ensembles and linear optics, *Nature (London)* **414**, 413 (2001).
- [2] K. Azuma, S. E. Economou, D. Elkouss, P. Hilaire, L. Jiang, H.-K. Lo, and I. Tzitrin, Quantum repeaters: From quantum networks to the quantum internet, *Rev. Mod. Phys.* **95**, 045006 (2023).
- [3] P. Kok, W. J. Munro, K. Nemoto, T. C. Ralph, J. P. Dowling, and G. J. Milburn, Linear optical quantum computing with photonic qubits, *Rev. Mod. Phys.* **79**, 135 (2007).
- [4] H. P. Specht, C. Nölleke, A. Reiserer, M. Uphoff, E. Figueroa, S. Ritter, and G. Rempe, A single-atom quantum memory, *Nature (London)* **473**, 190 (2011).
- [5] D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, Storage of light in atomic vapor, *Phys. Rev. Lett.* **86**, 783 (2001).
- [6] U. Schnorrberger, J. D. Thompson, S. Trotzky, R. Pugatch, N. Davidson, S. Kuhr, and I. Bloch, Electromagnetically induced transparency and light storage in an atomic Mott insulator, *Phys. Rev. Lett.* **103**, 033003 (2009).
- [7] J. J. Longdell, E. Fraval, M. J. Sellars, and N. B. Manson, Stopped light with storage times greater than one second using electromagnetically induced transparency in a solid, *Phys. Rev. Lett.* **95**, 063601 (2005).
- [8] 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).
- [9] Y.-F. Hsiao, P.-J. Tsai, H.-S. Chen, S.-X. Lin, C.-C. Hung, C.-H. Lee, Y.-H. Chen, Y.-F. Chen, I. A. Yu, and Y.-C. Chen, Highly efficient coherent optical memory based on electromagnetically induced transparency, *Phys. Rev. Lett.* **120**, 183602 (2018).
- [10] P. Vernaz-Gris, K. Huang, M. Cao, A. S. Sheremet, and J. Laurat, Highly-efficient quantum memory for polarization qubits in a spatially-multiplexed cold atomic ensemble, *Nat. Commun.* **9**, 363 (2018).
- [11] Y. Wang, J. Li, S. Zhang, K. Su, Y. Zhou, K. Liao, S. Du, H. Yan, and S.-L. Zhu, Efficient quantum memory for single-photon polarization qubits, *Nat. Photon.* **13**, 346 (2019).

- [12] M. Parniak, M. Dąbrowski, M. Mazelanik, A. Leszczyński, M. Lipka, and W. Wasilewski, Wavevector multiplexed atomic quantum memory via spatially-resolved single-photon detection, *Nat. Commun.* **8**, 2140 (2017).
- [13] 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).
- [14] L. Heller, P. Farrera, G. Heinze, and H. de Riedmatten, Cold-atom temporally multiplexed quantum memory with cavity-enhanced noise suppression, *Phys. Rev. Lett.* **124**, 210504 (2020).
- [15] X. Liu, J. Hu, Z.-F. Li, X. Li, P.-Y. Li, P.-J. Liang, Z.-Q. Zhou, C.-F. Li, and G.-C. Guo, Heralded entanglement distribution between two absorptive quantum memories, *Nature (London)* **594**, 41 (2021).
- [16] N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, Quantum repeaters based on atomic ensembles and linear optics, *Rev. Mod. Phys.* **83**, 33 (2011).
- [17] M. Cao, F. Hoffet, S. Qiu, A. S. Sheremet, and J. Laurat, Efficient reversible entanglement transfer between light and quantum memories, *Optica* **7**, 1440 (2020).
- [18] B. Zhao, Y.-A. Chen, X.-H. Bao, T. Strassel, C.-S. Chuu, X.-M. Jin, J. Schmiedmayer, Z.-S. Yuan, S. Chen, and J.-W. Pan, A millisecond quantum memory for scalable quantum networks, *Nat. Phys.* **5**, 95 (2009).
- [19] E. Saglamyurek, T. Hrushevskyi, A. Rastogi, L. W. Cooke, B. D. Smith, and L. J. LeBlanc, Storing short single-photon-level optical pulses in Bose-Einstein condensates for high-performance quantum memory, *New J. Phys.* **23**, 043028 (2021).
- [20] R. Zhao, Y. O. Dudin, S. D. Jenkins, C. J. Campbell, D. N. Matsukevich, T. A. B. Kennedy, and A. Kuzmich, Long-lived quantum memory, *Nat. Phys.* **5**, 100 (2009).
- [21] 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).
- [22] Y. O. Dudin, L. Li, and A. Kuzmich, Light storage on the time scale of a minute, *Phys. Rev. A* **87**, 031801(R) (2013).
- [23] J. Rui, Y. Jiang, S.-J. Yang, B. Zhao, X.-H. Bao, and J.-W. Pan, Operating spin echo in the quantum regime for an atomic-ensemble quantum memory, *Phys. Rev. Lett.* **115**, 133002 (2015).
- [24] B. Merkel, K. Thirumalai, J. E. Tarlton, V. M. Schäfer, C. J. Ballance, T. P. Harty, and D. M. Lucas, Magnetic field stabilization system for atomic physics experiments, *Rev. Sci. Instrum.* **90**, 044702 (2019).
- [25] X.-T. Xu, Z.-Y. Wang, R.-H. Jiao, C.-R. Yi, W. Sun, and S. Chen, Ultra-low noise magnetic field for quantum gases, *Rev. Sci. Instrum.* **90**, 054708 (2019).
- [26] A. Hesse, K. Köster, J. Steiner, J. Michl, V. Vorobyov, D. Dasari, J. Wrachtrup, and F. Jendrzejewski, Direct control of high magnetic fields for cold atom experiments based on NV centers, *New J. Phys.* **23**, 023037 (2021).
- [27] C. Cohen-Tannoudji and J. Dupont-Roc, Experimental study of Zeeman light shifts in weak magnetic fields, *Phys. Rev. A* **5**, 968 (1972).
- [28] S. H. Autler and C. H. Townes, Stark effect in rapidly varying fields, *Phys. Rev.* **100**, 703 (1955).
- [29] C. N. Cohen-Tannoudji, Nobel lecture: Manipulating atoms with photons, *Rev. Mod. Phys.* **70**, 707 (1998).
- [30] A. Leszczyński, M. Mazelanik, M. Lipka, M. Parniak, M. Dąbrowski, and W. Wasilewski, Spatially resolved control of fictitious magnetic fields in a cold atomic ensemble, *Opt. Lett.* **43**, 1147 (2018).
- [31] S. Chaudhury, A. Smith, B. E. Anderson, S. Ghose, and P. S. Jessen, Quantum signatures of chaos in a kicked top, *Nature (London)* **461**, 768 (2009).
- [32] M. Parniak, M. Mazelanik, A. Leszczyński, M. Lipka, M. Dąbrowski, and W. Wasilewski, Quantum optics of spin waves through ac Stark modulation, *Phys. Rev. Lett.* **122**, 063604 (2019).
- [33] C. Weitenberg, M. Endres, J. F. Sherson, M. Cheneau, P. Schauß, T. Fukuhara, I. Bloch, and S. Kuhr, Single-spin addressing in an atomic Mott insulator, *Nature (London)* **471**, 319 (2011).
- [34] S. Zhang, J. F. Chen, C. Liu, S. Zhou, M. M. T. Loy, G. K. L. Wong, and S. Du, A dark-line two-dimensional magneto-optical trap of ^{85}Rb atoms with high optical depth, *Rev. Sci. Instrum.* **83**, 073102 (2012).
- [35] M. Fleischhauer, A. Imamoglu, and J. P. Marangos, Electromagnetically induced transparency: Optics in coherent media, *Rev. Mod. Phys.* **77**, 633 (2005).
- [36] K. Reim, J. Nunn, V. Lorenz, B. Sussman, K. Lee, N. Langford, D. Jaksch, and I. Walmsley, Towards high-speed optical quantum memories, *Nat. Photon.* **4**, 218 (2010).
- [37] Y. Zuo, Z. Yujun, Y.-C. Chen, S. Du, and J. Liu, Scalability of all-optical neural networks based on spatial light modulators, *Phys. Rev. Appl.* **15**, 054034 (2021).
- [38] I. Moreno, J. A. Davis, T. M. Hernandez, D. M. Cottrell, and D. Sand, Complete polarization control of light from a liquid crystal spatial light modulator, *Opt. Express* **20**, 364 (2012).
- [39] D. A. Steck, Rubidium 85 D Line Data, available online at <http://steck.us/alkalidata> (revision 2.3.3, 28 May 2024).
- [40] Q.-Q. Hu, C. Freier, Y. Sun, B. Leykauf, V. Schkolnik, J. Yang, M. Krutzik, and A. Peters, Observation of vector and tensor light shifts in ^{87}Rb using near-resonant, stimulated Raman spectroscopy, *Phys. Rev. A* **97**, 013424 (2018).
- [41] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevResearch.6.L042002> for additional information on the experimental details of atom preparation, light storage and its limitations, AC beam shaping, AC Stark shift theoretical calculations, magnetic field profiles, and their effect on storage lifetimes.
- [42] T. Peters, Y.-H. Chen, J.-S. Wang, Y.-W. Lin, and I. A. Yu, Optimizing the retrieval efficiency of stored light pulses, *Opt. Express* **17**, 6665 (2009).
- [43] K. S. Choi, Coherent control of entanglement with atomic ensembles, Ph.D. thesis, California Institute of Technology, 2011.
- [44] L. Veissier, Quantum memory protocols in large cold atomic ensembles, Ph.D. thesis, Université Pierre et Marie Curie, 2013.
- [45] D. Felinto, C. W. Chou, H. de Riedmatten, S. V. Polyakov, and H. J. Kimble, Control of decoherence in the generation of photon pairs from atomic ensembles, *Phys. Rev. A* **72**, 053809 (2005).
- [46] J. Guo, X. Feng, P. Yang, Z. Yu, L. Chen, C.-H. Yuan, and W. Zhang, High-performance Raman quantum memory with

- optimal control in room temperature atoms, [Nat. Commun.](#) **10**, 148 (2019).
- [47] A. D. Tranter, H. J. Slatyer, M. R. Hush, A. C. Leung, J. L. Everett, K. V. Paul, P. Vernaz-Gris, P. K. Lam, B. C. Buchler, and G. T. Campbell, Multiparameter optimisation of a magneto-optical trap using deep learning, [Nat. Commun.](#) **9**, 4360 (2018).
- [48] M. Fleischhauer and M. D. Lukin, Dark-state polaritons in electromagnetically induced transparency, [Phys. Rev. Lett.](#) **84**, 5094 (2000).
- [49] K. Hammerer, A. S. Sørensen, and E. S. Polzik, Quantum interface between light and atomic ensembles, [Rev. Mod. Phys.](#) **82**, 1041 (2010).
- [50] T. Ozawa, H. M. Price, A. Amo, N. Goldman, M. Hafezi, L. Lu, M. C. Rechtsman, D. Schuster, J. Simon, O. Zilberberg, and I. Carusotto, Topological photonics, [Rev. Mod. Phys.](#) **91**, 015006 (2019).
- [51] N. R. Cooper, J. Dalibard, and I. B. Spielman, Topological bands for ultracold atoms, [Rev. Mod. Phys.](#) **91**, 015005 (2019).