

Controlled displacement of stored light at room temperatureArash Ahmadi,^{1,*} Yağız Murat¹,¹ Pei-Chen Kuan²,² Mustafa Gündoğan^{1,†} and Markus Krutzik^{1,3}¹*Institut für Physik and Center for the Science of Materials Berlin (CSMB), Humboldt-Universität zu Berlin, Newtonstrasse 15, Berlin 12489, Germany*²*Department of Physics, National Cheng Kung University, Tainan 70101, Taiwan*³*Ferdinand-Braun-Institut (FBH), Gustav-Kirchoff-Strasse 4, Berlin 12489, Germany*

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We report the demonstration of spatially translating a stored optical pulse at room temperature over distances exceeding one optical wavelength. By implementing an interferometric scheme, we further measure the average speed of this linear translation, thus harnessing a stopped-light experiment for a sensing application. This work extends the use of quantum memories beyond quantum communication and information contexts, opening a pathway to novel methods of velocity measurements with high sensitivity.

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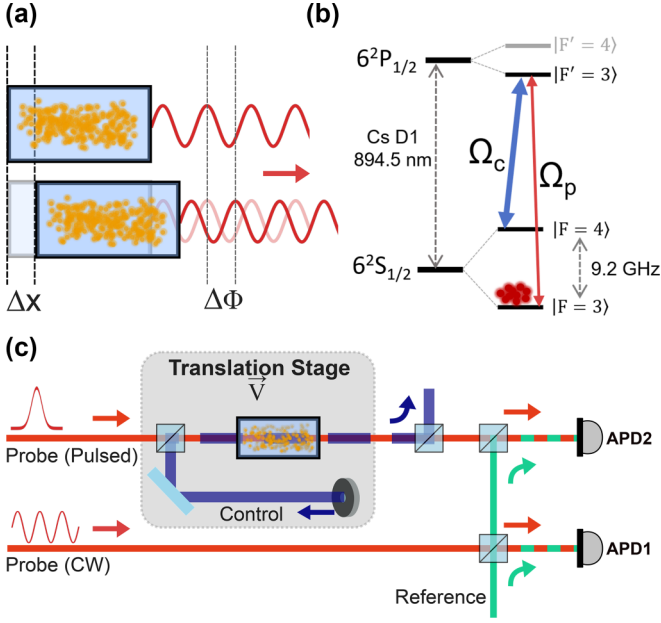
Quantum memories (QMs) are key elements of quantum information and communication systems, where precise control over both the storage and manipulation of information is essential for building scalable quantum networks [1–3]. Atomic ensembles are suitable for implementing such memories, as they exhibit high optical depth, tunable frequency range and long-lived spin states, leading to high storage efficiency, extended storage durations, and robust phase coherence. Electromagnetically induced transparency (EIT) in a Λ – type three-level atomic system has become one of the most established methods to realize such memories [4], and has been implemented in cryogenic solid-state systems [5,6], ultracold and cold atomic ensembles [7–12], and warm alkali vapors [13–15]. Notably, the phase of the retrieved signal can be directly measured and compared to that of the stored pulse [16,17], thereby enabling the exploitation of this phase information to monitor additional parameters, such as the spatial displacement of the stored light, during the storage process. Such an ability is beneficial, as physical reconfiguration of atomic arrays can enhance quantum processing [18], and transport of quantum memories to improve quantum communication [19] and astronomical interferometry [20] has been proposed.

The idea of storing light in a moving atomic medium and retrieving it at a different location has long been proposed [21]. Here, the continuous wave (CW) control fields are launched perpendicular to the direction of the moving medium, and the passage of atoms through the optical fields define the adiabatic switching of the control field on and off.

Such a configuration is helpful in cases that the arrival of the probe pulse cannot be fully determined, e.g., it is originated in spontaneous processes. However, the other features of the storage process, the pulse profiles, storage time, etc., cannot be controlled. On the other hand, it has been experimentally shown that spin coherence in warm alkali vapor can diffuse over extended spatial regions without dephasing [22,23]. However, in these studies, the spatial displacement of the stored information is not actively controlled and relies on the random motion of the atoms. Ginsberg *et al.* [24] were the first to demonstrate the transfer of stopped light, storing an optical pulse in a Bose–Einstein condensate (BEC) and subsequently transferring it to another BEC located 160 μm away. Furthermore, the preservation of spin coherence during macroscopic displacement in an optical conveyor belt [25,26] paved the way for transporting stored light in cold atoms confined by an optical lattice [27], where a stored optical pulse was displaced in a controlled manner through a hollow-core fiber over a distance $\Delta x = 1.2\text{ mm}$.

In this Letter, we report on the controlled transport of an optical pulse stored within an alkali vapor cell. We furthermore infer information on the displacement of the stored pulse by monitoring its phase before and after the storage process. Figure 1 illustrates both the experimental setup and the fundamental measurement principle. The phase of the retrieved pulse is unchanged in the reference frame of the QM, but not in the laboratory frame. When the vapor cell is moved in space, comparing the phase of the retrieved pulse to that of a reference field leads to measuring the traveled distance. Light storage is accomplished via implementation of resonant EIT in the D1 line of cesium. The Λ -type atomic scheme consists of the ground states $|F = 3\rangle$ and $|F = 4\rangle$, and the excited state $|F' = 3\rangle$. A strong control field, offset-locked to the $|F = 4\rangle - |F' = 3\rangle$ transition, establishes the transparency condition. A small fraction of this control beam is frequency-shifted by 9.2 GHz using an electro-optic modulator (EOM) to resonate with the $|F = 3\rangle - |F' = 3\rangle$ transition, thus forming the probe beam. This method ensures an intrinsically

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high phase coherence between the probe and control fields. Pulse shaping is achieved through acousto-optic modulators (AOMs), driven by an arbitrary waveform generator (AWG). The probe and control beams have diameters of 1 mm and 2 mm, with peak powers $P_P = 50 \mu\text{W}$ ($\Omega_P = 2\pi \times 7 \text{ MHz}$) and $P_C = 10 \text{ mW}$ ($\Omega_C = 2\pi \times 70 \text{ MHz}$), respectively.

The vapor cell, containing 10 Torr of nitrogen (N_2) buffer gas, is housed within two layers of μ -metal magnetic shielding and heated to 45°C to reach an optimal optical density. The entire cell assembly is mounted on a translation stage with a minimum incremental motion of 1 nm. To precisely measure the phase shift of the probe pulse, we generate a reference field by passing the probe through an AOM, shifting its frequency by 80 MHz. Prior to pulsing the probe beam and guiding it to the vapor cell, a portion of the probe beam is beaten with this reference field and creates a CW 80 MHz beat signal. This beat signal is then detected by an avalanche photodiode (APD1) and provides a stable reference for measuring the phase shift. This reference beat signal practically acts as a ruler to infer the displacement of the vapor cell during light storage. In order to monitor the phase shift in the storage process, a portion of the reference field is beaten with the probe field after the vapor cell and prior to its detection by a second avalanche photodiode (APD2). This generates an

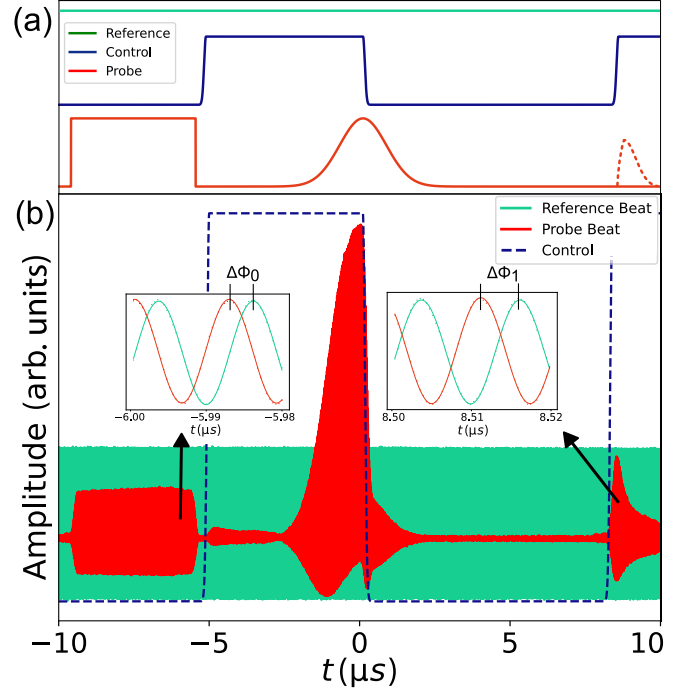


FIG. 2. Light storage and phase detection. (a) The respective pulse sequences. The dashed pulse in the probe panel illustrates the retrieval of the stored pulse. (b) An actual trace from the oscilloscope. The CW beating signal (green) acts as a ruler for measuring changes in phase. The probe pulse sequence (red) consists of a square pulse (as baseline phase) and a Gaussian pulse (to be stored). The insets show 20 ns long traces at $t = -6 \mu\text{s}$ (to measure $\Delta\Phi_0$) and $t = +8.5 \mu\text{s}$ (to measure $\Delta\Phi_1$).

intrapulse 80 MHz beat signal, which enables the accurate measurement of the phase evolution of the retrieved pulse relative to the input pulse during the motion of the translation stage. Both the CW reference beat and the probe intrapulse beat signals can be viewed as being generated from two Mach-Zehnder interferometers (MZI) consisting of the probe field and the reference field; with the difference that for the latter, the probe beam is pulsed and goes through the vapor cell. More details on the laser assembly, pulse shaping and light storage is provided in the Supplemental Material [28].

Figure 2(a) shows the pulse sequence of the storage process and Fig. 2(b) shows an actual trace of the detected light fields on the oscilloscope. The green background curve shows the reference beat signal, the red curve demonstrates the detected probe pulse, carrying an intrapulse beating, and the dashed line indicates the intensity profile of the control field. The control field is turned on at $t = -5 \mu\text{s}$ (pumping atoms to $|F = 3\rangle$ and preparing the EIT conditions) and is adiabatically switched off at $t = 0 \text{ s}$. After a storage time $\tau_s = 8.5 \mu\text{s}$, it is switched back on again to retrieve the stored pulse from the atomic ensemble. Prior to activating the control field, the probe is switched on for a short duration. The phase of the probe field may fluctuate from shot to shot due to mechanical vibrations and the laser's finite coherence length; therefore, this initial pulse is essential and provides us with a baseline phase difference $\Delta\Phi_0$ between the background beat signal and the probe field. It is important to note that $\Delta\Phi_0$ is mea-

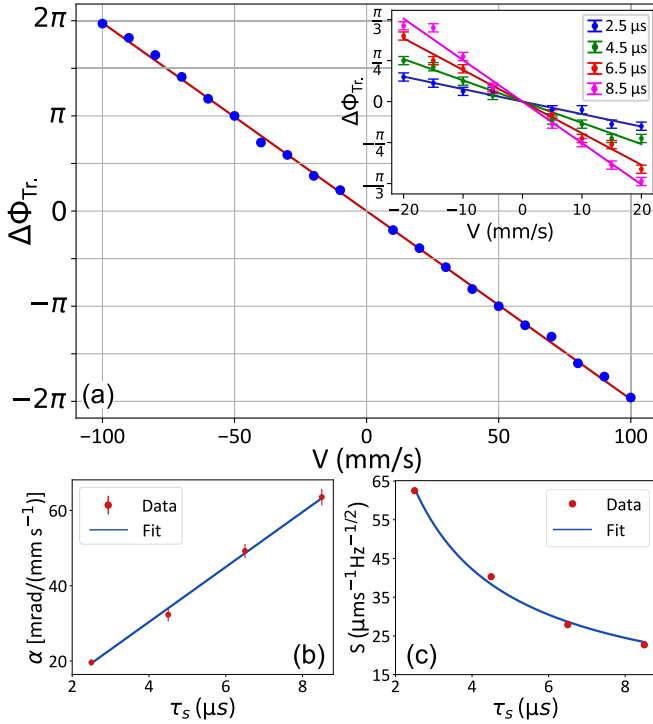


FIG. 3. Spatial transport of stored light. (a) Measured phase shift vs. stage speed, for $\tau_s = 8.5 \mu\text{s}$. The stored pulse is translated a full wavelength on either direction with $\Delta\Phi_{\text{Tr}} = \pm 2\pi$. The inset shows the same measurement for different storage times. (b) Plot of coefficient α vs. τ_s . The fitted line has a slope $m = 7.31 \pm 0.33 \text{ mrad/nm}$, which matches the expected $k_P = 7.02 \text{ mrad/nm}$. (c) Calculated sensitivity of the setup when used as a velocimeter.

sured in the absence of EIT, where light-drag effects [29] are negligible. After the control being on for $2.5 \mu\text{s}$, a $2 \mu\text{s}$ Gaussian-shaped probe pulse is sent into the vapor cell. Its timing is aligned with the onset of the control field's switch-off, ensuring optimal overlap for maximum storage efficiency.

After retrieval of the stored pulse, the phase of the retrieved pulse is compared with that of the background beat and labeled as $\Delta\Phi_1$. We can define the phase evolution of the probe field (P) during storage process as

$$\Delta\Phi_P^{R/M} \equiv \Delta\Phi_1^{R/M} - \Delta\Phi_0^{R/M} \quad (1)$$

with R and M indicating the cases when the stage is at “Rest” or in “Motion”, respectively. Now, if we measure a $\Delta\Phi_P^R$ and subsequently a $\Delta\Phi_P^M$ for some storage time τ_s , we can define the phase shift due to this translation (Tr.) as

$$\Delta\Phi_{\text{Tr.}} \equiv \Delta\Phi_P^M - \Delta\Phi_P^R = -\vec{k}_P \cdot \Delta\vec{x} = -\vec{k}_P \cdot \vec{V}\tau_s \quad (2)$$

where $\vec{V}$ is the average velocity of the translation stage during storage, resulting in a displacement of $\Delta\vec{x} = \vec{V}\tau_s$ for the vapor cell—and thus the stored pulse.

Figure 3(a) shows the resulting phase shift for different velocities, from -100 mm/s to $+100 \text{ mm/s}$, with $\tau_s = 8.5 \mu\text{s}$. As expected, the measured phase shift exhibits a linear relation to V , i.e., $\Delta\Phi_{\text{Tr.}} = -\alpha V$, with $\alpha = 63.6 (\pm 2.2) \text{ mrad/(mm.s}^{-1})$. Observing phase shifts up to $\pm 2\pi$ means that the stored pulse has been displaced by

$\Delta x = \lambda_P$ on either direction, with λ_P being the wavelength of the probe field. Moreover, it is possible to track the displacement of the stored pulse anywhere between these two extremes.

Even though derived from different physical principles, the phase shift observed in our setup, Eq. (2), follows the same mathematical description as that of EIT-enhanced light-drag [30–33], with the delay time τ_d replaced with storage time τ_s . Hence, in a similar manner, this relation can be exploited to create a velocimeter. In order to fully verify the validity of Eq. (2) in our setup, we have repeated this measurement for other storage times, $\tau_s = [2.5 \mu\text{s}, 4.5 \mu\text{s}, 6.5 \mu\text{s}, 8.5 \mu\text{s}]$, with stage velocities in the range $(-20 \text{ mm/s}, +20 \text{ mm/s})$. The corresponding results are presented as the inset of Fig. 3(a), which shows clear increase in the steepness of the plots as the storage time increases. Figure 3(b) shows the plot of α vs. τ_s , following a linear trend with the slope $m = 7.31 (\pm 0.33) \text{ mrad/nm}$, covering the actual wave number of the probe $k_P = 7.02 \text{ mrad/nm}$. In each measurement, the oscilloscope trace is averaged 16 times and the phase shift is averaged over 20 runs. For the case of $\tau_s = 8.5 \mu\text{s}$, this results in a total integration time $T = 6.9 \text{ ms}$. The calculated standard error of the phase shift $\delta\Phi = 17.4 \text{ mrad}$, equivalent to a velocity resolution of $\Delta V \approx 270 \mu\text{m/s}$. This translates to a short-term sensitivity (S) of $22.7 \mu\text{m s}^{-1} \text{ Hz}^{-1/2}$. Figure 3(c) shows the plot of S vs. τ_s . The fitted line follows the equation $S = \frac{\delta\Phi}{k_P \tau_s} \sqrt{T}$, where integration time $T = \beta(\tau_s + \varepsilon)$, with β representing the total number of pulse sequences considered in each data point (oscilloscope averaging $\times$ measurement runs), and ε representing length of the pulse sequence excluding the storage duration. As the storage time is increased, the sensitivity also improves, following a $1/\sqrt{\tau_s}$ trend.

The phase fluctuation in our setup is 4 orders of magnitude worse than the ultimate photon shot-noise limit, 17.4 mrad vs. $8.3 \mu\text{rad}$. However, our achieved resolution in velocity measurement is comparable to that of the usual laser doppler velocimeters [34–36] and EIT-enhanced longitudinal light-drag measurements [30,31]. It is worth to mention that our acquired values are not the ultimate performance of this scheme, since extending the storage time and improving the phase stability of the interferometer can significantly increase the velocimetry resolution. However, the current experimental setup imposes certain limitations on further enhancing the sensitivity. Presently, the storage time is limited to $8.5 \mu\text{s}$. Extending this duration would require improved magnetic shielding, since the translation stage is highly magnetic. Furthermore, the laser used has a short-term linewidth of $\sim 100 \text{ kHz}$, which limits its temporal coherence to about $10 \mu\text{s}$. As a result, the temporal separation between the baseline and retrieved pulses should not significantly exceed $10 \mu\text{s}$; otherwise, the measured phases ($\Delta\Phi_0$ and $\Delta\Phi_1$) would no longer be reliably comparable. Nevertheless, reducing the natural linewidth of the laser to below 1 kHz is well established [37], thereby extending the laser's coherence time to the millisecond range. This time scale fits well with the storage times achievable with vapor cells in compact and relatively simple memory setups [38]. Since the beating signal is generated via a MZI without any active stabilization, the phase relation between the probe and reference fields fluctuates from shot to shot, and averaging the trace of the oscilloscope beyond

16 times reduces the actual phase stability. At this limit, measurement bandwidth reaches the usual frequency associated to ambient mechanical vibrations (~ 100 Hz). Therefore, active phase stabilization of the reference beat note with respect to the probe beat note is a necessary step moving forward. As an estimate, by stabilizing the phase drift of the MZI to below 1 degree [39] and extending the storage to 1 ms, our sensitivity could be enhanced by 3 orders of magnitude to $S = 20 \text{ nm s}^{-1} \text{ Hz}^{-1/2}$.

In summary, we have reported on spatial displacement of a stored pulse in a warm alkali vapor cell. Moreover, by monitoring the phase of the retrieved pulse, we were able to accurately track the displacement of the stored pulse up to one optical wavelength along both $\pm \hat{z}$ directions. This method can be utilized as an effective motion sensor, as explored in our previous work [40]. The findings open new avenues for more complex implementations of quantum memories in warm

vapors and offer applications beyond traditional domains such as quantum information and communications.

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Data availability. The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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