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Concept for motion sensing using atomic optical memories

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Abstract

By harnessing optical memories based on electromagnetically induced transparency in warm vapors of gaseous alkali metals and cold atomic clouds, this article presents new methods for motion sensing. The proposed scheme for velocimetry can substantially increase the sensitivity of some recent works based on the light-dragging effect in a moving medium, and on the other hand, our proposal, when realized using cold atoms, opens new research questions with regard to limits of light storage in cold atomic clouds. Ultimately, a detailed experimental setup is presented for the realization of the velocimetry scheme using stopped light, which includes considerations for the choice of the medium, laser configuration and control. By investigating the limits of optical memories in motion sensing applications, this research opens up new avenues for employing optical memories beyond applications in quantum information science.

1. Introduction

Quantum memories (QM) are fundamental components in quantum communication and quantum computation (Heshami et al., 2016), and significant research has been conducted to realize and develop them in various media and physical systems for the storage of either single photons or classical optical pulses (Wu et al., 2013; Chen et al., 2013; Saglamyurek et al., 2015; Gündogan et al, 2015; Esguerra et al., 2023). Focusing on alkali metal atomic ensembles, such optical memories have been realized by employing various schemes (Riedl et al., 2012; Chen et al., 2013; Guo et al., 2019; Saglamyurek et al., 2021), among which, electromagnetically induced transparency (EIT) in warm vapor cells of cesium or rubidium has exhibited high levels of storage efficiency (Hosseini et al., 2011) and storage times up to 1 s (Katz and Firstenberg, 2018), extending the limits of optical memories for applications at room temperature.

On the other hand, motion sensing based on optical interferometry is a well-established technique (Yeh and Cummins, 1964; Foreman et al., 1965; Gusmeroli and Martinelli, 1991; McKenzie, 1996). Recently, EIT has been employed to measure the velocity of a moving medium, leveraging Fizeau's light-dragging effect (Kuan et al., 2016; Chen et al., 2020). Based on the light-dragging effect, as an optical field passes through a moving medium, dispersion leads to a phase shift proportional to the velocity of the medium, that is, $\Delta\phi = F_d V$, with F_d being the dragging coefficient and V being the medium's velocity. In terms of the refractive index of the medium and its dispersion, the dragging coefficient can be written as $F_d = 1 - 1/n^2 + (\omega/n)[\partial n/\partial\omega]$, with n being the refractive index of the medium and ω being the frequency of the light. In the usual dispersive media $F_d \sim 1$, which means for low velocities, the resulting phase shift becomes challenging to detect. In EIT, the dispersion of the medium is enhanced by orders of magnitude, while, simultaneously, the absorption of the optical field is suppressed, leading to a more significant light-dragging effect. This development has opened up new possibilities for utilizing quantum optical methods, such as light storage in optical memories, in motion sensing.

In this article, we propose a novel method of motion sensing employing optical memories based on EIT in cold and warm alkali gases. Realizing this proposal helps to extend the use of optical memories in quantum sensing (Ajoy et al., 2015; Zaiser et al., 2016) and would test the limits of these systems for applications beyond quantum information science. This paper is organized as follows: in section "Enhancing light-dragging using EIT," we outline how EIT can be used to enhance the light-dragging effect. This is followed by section "Velocimetry using light storage," where we propose a scheme of velocimetry based on light storage in warm vapors focusing on phase coherence in light storage, as well as the extent to which a vapor cell in motion can efficiently store and retrieve an optical pulse. Attempting to extend these limits can significantly enhance the sensitivity of motion sensing based on slowed light in EIT. In section "Gravimetry using light storage in ultra-cold atomic clouds," we propose utilizing light storage

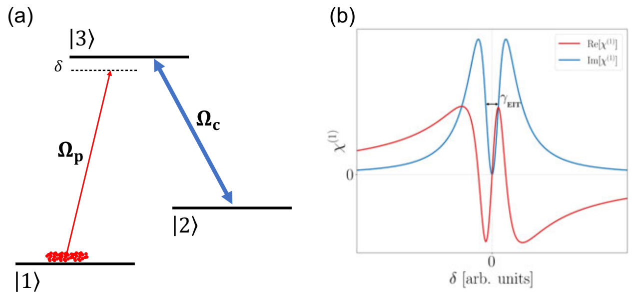

Figure 1. Electromagnetically induced transparency. a) The relevant Λ-scheme and b) dispersion (red) and absorption (blue) characteristics, which are related to the real and imaginary parts of the susceptibility, respectively. See text for details.

in cold atomic clouds in a regime where the number of photons in an optical pulse approaches the number of atoms in the cloud, that is, $n_{photons} \sim n_{atoms}$.

2. Enhancing light-dragging using EIT

EIT can be implemented by coupling two ground states, $|1\rangle$ and $|2\rangle$ to a mutual excited state, $|3\rangle$, in a Λ-scheme (Fleischhauer et al., 2005).

Here, Ω_p and Ω_c are the Rabi frequencies of the probe and control field, coupling the ground states $|1\rangle$ and $|2\rangle$ to a common excited state $|3\rangle$, with frequencies ω_p and ω_c, respectively. The probe field has a detuning δ, which is used to scan the frequency of the probe field and observe the EIT phenomenon, Figure 1(a). The EIT condition is satisfied by having $\Omega_p \ll \Omega_c$, where sweeping ω_p around the resonance reveals a narrow frequency window where the medium exhibits full transparency. The transparency window has a linewidth $\gamma_{EIT} = \gamma_{12} + |\Omega_C|^2/\gamma_{13}$, where $\gamma_{12/13}$ is the decay rate between states $|1\rangle - |2\rangle$ and $|1\rangle - |3\rangle$. In this condition, the medium simultaneously exhibits high dispersion and low absorption, Figure 1(b), leading to a large dragging coefficient, that is, $F_d > 1$. This high dispersion also leads to a reduced group velocity of the probe field (Fleischhauer and Lukin, 2000):

$$v_g = \frac{c}{1 + \frac{g^2 N}{\Omega_c^{\,2}}} \tag{1}$$

where g is the coupling strength and N is the number of atoms. Fine-tuning the ratio $\frac{\Omega_p}{\Omega_c}$ (Kash et al., 1999), as well as increasing the number of atoms (Strekalov et al., 2004), that is, optical depth, can result in extremely slow group velocities in the probe field, and a slow group velocity means the possibility of compressing a spatially extended optical pulse within a few-centimeter-long vapor cell.

In this regime, the accumulated phase caused by light drag can be calculated from the formula (Davuluri and Rostovtsev, 2012; Kuan et al., 2016; Chen et al., 2020):

$$\phi = -\frac{k_0 V L}{v_g} = -k_0 v \tau_d \tag{2}$$

where k_0 is the wave vector of light in the lab frame, L is the interaction length of the medium and $\tau_d \equiv L/v_g$ is the time light spends in the medium. However, since the time delay $\tau_{delay} \sim 100\mu s$ (Strekalov et al., 2004; Kuan et al., 2016; Safari et al., 2016; Chen et al., 2020), detecting the phase shift from the dragging effect when dealing with slow medium velocities, $V \ll 1$, becomes extremely challenging.

3. Velocimetry using light storage

In velocimetry using EIT (Kuan et al., 2016; Chen et al., 2020], the Fizeau's light-dragging effect is at the core of the process, and the phase shift results from the change in the phase velocity of light as the medium moves; EIT enhances this effect by increasing the dispersion of the medium and reducing the group velocity of the probe field; therefore, the delay time τ_d is significantly increased. In addition to reducing the speed of light, EIT also allows the light pulses to be completely halted and stored in the medium for some storage time τ_s. In our proposed method, the measurement of the phase shift in the beat note is similar to the previous works; however, by leveraging light storage in atomic media, the phase shift is rooted at a fundamentally different physical phenomenon. The setup proposed here measures the phase shift of the beating signal by comparing the phase of the signal at two separate spatial points along a reference field. The process may be thought of as a delayed imbalanced Mach–Zehnder interferometer, such that the length of the delay arm is set by the storage time and the phase evolution of the probe field in the delay arm is set by the phase coherence of the control field and the storage process. In spite of this difference, it will be seen that the mathematical description for measuring the velocity of the moving medium remains the same, giving us a framework for comparing the sensitivity of the two methods.

In order to store an optical pulse using EIT, once the probe pulse is compressed within the medium, the control field is adiabatically switched off. This process converts the input photonic excitation to a coherence between the ground states $|1\rangle$ and $|2\rangle$, also called a dark-state polariton (Fleischhauer and Lukin, 2000). The retrieval is the time reversal of this process: control field is adiabatically switched back on, and the stored excitation is converted back to an optical field, which then leaves the medium along its initial direction (Phillips et al., 2001; Liu et al., 2001]. The storage time in this scheme depends on several factors, such as ground state decoherence rate, electric and magnetic field noise and optical beam diameters in warm gases (Finkelstein et al., 2023]. The phase information has been shown to be preserved and coherently retrieved during writing and retrieving the optical pulse (Mair et al., 2002]. Furthermore, precise measurement and control of the phase of the retrieved pulse have been demonstrated (Park et al., 2016; Jeong et al., 2017). These features make EIT-based optical memories suitable tools for utilizing optical interferometry in developing displacement sensors.

Spatial transport of stored optical pulses (Li et al., 2020) has led to new proposals for quantum communications (Gündoğan et al., 2024). In our proposed method, displacement is detected by storing the probe field in a moving alkali vapor cell and monitoring the phase of an optical beating signal between the probe field and a reference field, which is detuned far enough not to be affected by the EIT condition. Before entering the medium, the phase of the beating signal is initially detected by the photodetector D_I. The control field is launched simultaneously, creating the conditions for light storage. At this moment, the probe field is stored for a storage time τ_s; meanwhile, the medium moves at some average speed V, resulting in a displacement of $\Delta x = V\tau_s$. The probe field is retrieved after τ_s, and the phase of the beat signal is then detected by the second detector D_{II}. During this process, the phase of the beating signal is influenced by both the storage time and

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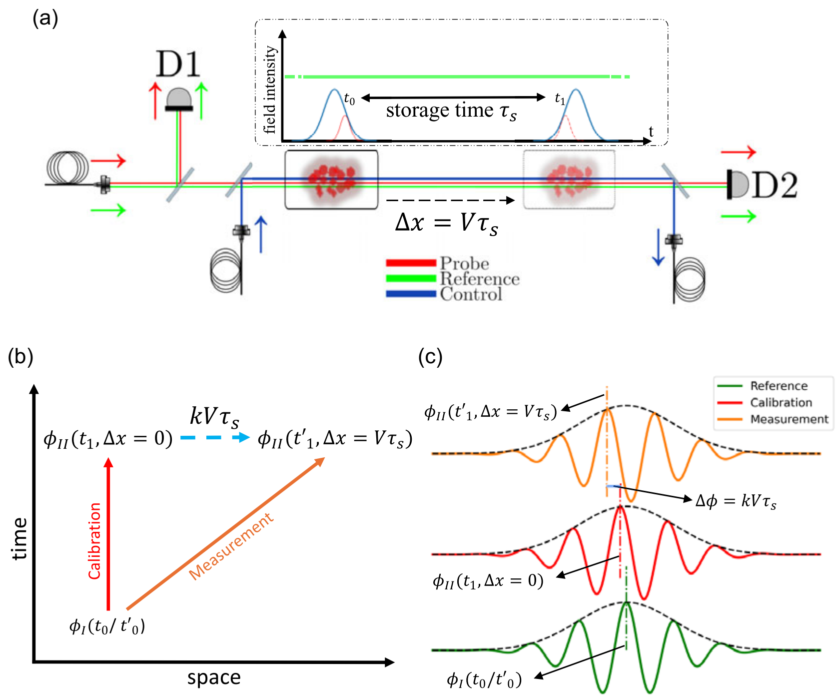

Figure 2. Setup and the theory scheme. a) Schematic of the optical setup. The inset shows the pulse sequence matched with the position of the vapor cell. b) A time-space visualization of the velocimetry protocol: detector D_I records the phase of the beating signal at times t_0 or t'_0; depending on the movement of the vapor cell, the time of the recorded phase of by detector D_{II} is labeled as t_1 or t'_1; comparing phase shifts in the time window of $t_0 \rightarrow t_1$ and $t'_0 \rightarrow t'_1$ will reveal the displacement of the cell and hence its velocity. c) In each step of the protocol in "b," the phase of the beating signal is measured with respect to the symmetry point of the pulse profile. The velocity of the moving medium is then calculated by comparing these different measured phases.

the medium's displacement, which can be measured by comparing the phase of the detected signals. In order to have a high efficiency in storing the probe pulse and reading the phase of the beating signal, two factors should be considered: first, the bandwidth of the probe field pulse should be narrow enough to fall into the EIT linewidth γ_{EIT} and, simultaneously, much higher than the frequency of the beating signal, to include sufficient number of oscillations for phase measurements. The schematic of the proposed setup is presented in Figure 2(a).

Figure 2(b) shows the principle underlying the stopped light velocimetry. The process can be split into two steps. In the first step, at time t_0, the beating signal between the probe field and the reference field is detected by D_I, and the phase information is recorded as $\Phi_I(t_0)$. This phase information sets a reference point, relative to which, all the changes in the phase of the beating signal can be measured. Simultaneous with this initial phase measurement, the light is stored in the vapor cell; after a storage time of τ, without moving the cell, the phase information of the beating between the retrieved pulse and the reference field will be detected by D_{II}, and recorded as $\Phi_{II}(t_1, \Delta x = 0)$, where $t_1 = t_0 + \tau_s$. Any change in the phase, as compared with the reference phase $\Phi_I(t_0)$, will reveal the phase accumulation during the light storage coming from the beating frequency and the inner dynamics of the storage process (Jeong et al., 2017; Katz and Firstenberg, 2018). We call this step the **calibration step**:

$$\Delta\Phi_{Cal.} \equiv \Phi_{II}(t_1, x_0 \Delta x = 0) - \Phi_I(t_0) \tag{3}$$

$\Phi_{Cal.}$ is only dependent on τ_s and sets our next reference point for measuring the influence of the motion of the stage. In the next step, the phase of the beating signal is again detected at detector D_I at time t'_0 and simultaneously stored in the medium. However, this time, during the storage time τ_s, the vapor cell is moved at a constant speed V, ending up in the position $x_0 + V\tau_s$. After retrieval of the stored light, the phase of the beating signal between the probe field and the reference field is measured at the second detector and the phase information $\Phi_{II}(t'_1, \Delta x = V\tau_s)$, where $t'_1 = t'_0 + \tau_s$ is recorded. We name this step the **measurement step**:

$$\Delta\Phi_{Meas.} \equiv \Phi_{II}(t'_1, \Delta x = V\tau_s) - \Phi_I(t'_0) \tag{4}$$

As indicated in Figure 2(b), the difference between $\Delta\Phi_{Meas.}$ and $\Delta\Phi_{Cal.}$ should only be originating from the movement of the vapor cell:

$$\Delta\Phi_{Meas.} - \Delta\Phi_{Cal.} = kV\tau_s \tag{5}$$

with k being the wave vector of the reference field. Figure 2(c) shows a hypothetical phase measurement sequence. The "reference" curve (green) shows the beating signal as it is recorded by D_I at times t_0 or t'_0. For simplicity, the curves for these two instances are plotted with the same phase. The "calibration" curve (red) is the recorded beating signal by D_{II} at time t_1. The "measurement" curve (orange) is the recorded beating signal by D_{II} at time t'_1. By knowing the phase shift in the calibration step, one can calculate the phase shift purely resulted from the movement of the cell. Comparing Equations 2 and 5, it is clear that, in both cases, the sensitivity in measuring the velocity is inversely proportional to the storage/delay time, that is, $\delta V \propto \tau_{s/d}$. The EIT delay times reported in the literature are usually in the range of ~ 10μs – ~ 100μs (Chen et al., 2017,2020; Kash et al., 1999; Xiao et al., 2008), whereas the range for storage time of optical pulses in these media can lie in the range of $\sim 1ms - 1\,s$ (Katz and Firstenberg, 2018; Wang et al., 2022). Comparing these two time ranges indicates that by using the light storage protocol instead of only delayed light, in principle, this sensitivity can be enhanced by several orders of magnitude.

4. Potential implementation

In this section, we demonstrate in detail the features of a suitable experimental setup for testing the proposed velocimetry scheme using alkali warm vapor. At the heart of the setup is a warm vapor

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cell of an alkali metal, and, among different options, the D1 transition lines of ^{133}Cs and ^{87}Rb offer suitable conditions with sufficient energy splitting between the excited levels so that the competing EIT paths of the overlapping excited states do not affect the EIT visibility (Mishina et al., 2011; Scherman et al., 2012). Besides the choice of the alkali metal, the buffer gas filling the vapor cell can play an important role in order to reduce the diffusion of the atoms outside of the optical fields, as well as decoherence due to inelastic collisions between the alkali atoms (McGillis and Krause, 1967; Reim et al., 2011). Several studies show that noble gasses or molecular nitrogen with pressures ranging from 10 to 30 Torr improve the performance of such optical memories (Thomas et al., 2017; Wang et al., 2022). For containing the alkali metal vapor and the buffer gas, usually, quartz cells with wedged walls attached at an angle are used. The walls are wedged in order to minimize the interference effects due to surface reflections; however, such a wedge deflects the path of the beam as it passes through the cell walls, leading to off-axis displacement of the retrieved light as the cell moves forward. Therefore, for the suggested setup, having a vapor cell with wedged walls should be avoided. The cell is placed inside a holder designed to hold heaters and thermostats to control and monitor the temperature of the cell and achieve the desired optical depth. Shielding the medium from the noisy electromagnetic fields in the surrounding is another key factor in obtaining an efficient optical memory. Enclosing the vapor cell in two layers of concentric cylindrical $\mu-$metals, with dimension carefully chosen to minimize surrounding electromagnetic fields in the transverse direction (Dubbers, 1986), could create the sufficient conditions for achieving storage times close to 1 ms in a compact and portable setup (Wang et al., 2022). In order to mimic the movement of the medium, automated translation stages with minimum incremental motion as low as $\Delta x \sim 1$nm is available in the market and can test the precision of the proposed scheme down to nm/s scale.

In order to realize the $\Lambda-$scheme EIT in the D1 transition a strong control field, $P \sim$ mW, on the $F = 4 \leftrightarrow F' = 3$ transition in Cs or on the $F = 2 \leftrightarrow F' = 1$ in Rb, and a weak probe field, $P \sim \mu$W, on the $F = 3 \leftrightarrow F' = 3$ or $F = 1 \leftrightarrow F' = 1$, in Cs and Rb, respectively, can be tuned. Two separate lasers can be used to achieve better tunability of the control and probe field frequency and energies. Using frequency modulation spectroscopy (Bjorklund et al., 1983), one low-power "primary" laser can be locked to the transition aimed for the probe field; then, a second high-power "secondary" laser will be offset-locked (Ivanov et al., 2011) to the primary laser, with an offset frequency matching the hyperfine splitting of the ground state in the D1 transition, 6.8GHz & 9.2GHz for Rb and Cs, respectively. This way, the secondary laser can act as a strong control field. The probe field can be obtained by using an electro-optical modulator (EOM), with the modulation frequency equal to the splitting of the ground states. The secondary laser passes through the EOM and then a high finesse cavity to get a clean side band with the energy matching to that of the probe field. This way, the phase coherence between the two optical fields is guaranteed, and any fluctuation in the wavelength of the laser does not alter the EIT conditions, as both control and probe field are tied together (Li et al., 2020). On the other hand, the proposed scheme relies on having a strong coherence between the phase of the stored and retrieved pulse. As it has been shown (Park et al., 2016; Jeong et al., 2017; Katz and Firstenberg, 2018), the phase of the retrieved pulse is directly controlled by the phase of the control field at the moment of retrieving the stored pulse from the memory. Therefore, the maximum limit of storage time for extending the sensitivity of the velocimeter is inversely proportional to the linewidth of the laser used for the control and probe fields. External cavity diode lasers usually have a linewidth of ~ 100 kHz, within ~ 10 ms. Such a linewidth translates into a time window of $\sim 10\mu$s. At this stage, the main limiting factor of the motion sensor is not the storage time of the memory, but rather the linewidth of the laser used. Nevertheless, different methods have managed to reduce the linewidth down to sub-kilohertz (Ludlow et al., 2007; Saliba and Scholten, 2009; Torrance et al., 2016), which pushes the limit on the storage time beyond 1 ms, which is more or less the range achievable with a warm vapor optical memory based on resonant EIT (Wang et al., 2022).

Lastly, similar to the setup in Chen et al. (2020), the vapor cell can be placed on a motorized moving stage with motion precision on a nanometer scale, and in order to measure the phase shift due to the movement of the cell, two high-dynamic range detectors, before and after the moving medium, can be used to detect the weak beat note of the probe+reference field. By comparing the RF signal from the detectors on an oscilloscope, the phase shift can be measured according to the protocol described in section "Velocimetry using light storage."

5. Gravimetry using light storage in ultra-cold atomic clouds

Here, we propose to use the same protocol presented in section "Velocimetry using light storage" for measuring local gravitational acceleration. The principle behind the measurement and the experimental steps will remain basically the same; however, the vapor cell will be replaced by a cold atom cloud, similar to atom interferometry gravimeters. The atom cloud would be held fixed at a position h_0, and the calibration step is conducted by measuring the phase of the beating signal before the signal reaches the cloud and then after storage and retrieval of the probe field in the atoms. In the next step, the phase shift of the beat signal during storage is measured, while the atom cloud is released at the moment of storage. Similar to the analysis given in section "Velocimetry using light storage," the change in the phase between the two steps in related to the vertical displacement of the atomic cloud:

$$\Delta\Phi_{Meas.} - \Delta\Phi_{Cal.} = k\Delta h = \frac{1}{2}kg\tau_s^2. \tag{6}$$

It is worthwhile to draw some comparisons between this proposed scheme and the well-established Mach–Zehnder type atom interferometry used for gravimetry (Kasevich and Chu, 1991, 1992; Peters et al., 1999, 2001), in which the phase shift due to the fall of the atom cloud amounts to $\Delta\Phi = kg(T/2)^2$, with T being the total fall time. In comparison, in our proposal, the storage time $\tau_s \equiv T$; therefore, for an equal fall duration, the accumulated phase in our proposed setup is twice as big as the usual atom interferometry method. Moreover, the physical principle behind this concept is similar to the usual classical approach to gravimetry, that is, the free-falling corner-cube gravimeters (Alasia et al., 1982; Faller and Marson, 1988), which relies on a Michelson-type interferometry and tracks the vertical location of a free-falling object, and hence its gravitational acceleration, by monitoring the changes in the phase of the fringe pattern. However, due to the negligible mass of the free-falling atom cloud, it can be immune to some systematic errors faced by the free-falling corner cubes, such as self-attraction or recoil, which can limit the sensitivities of such gravimeters to reach the ultimate shot noise limit (Niebauer et al., 1995, 2012). Free-falling Bose–Einstein condensates could be

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suitable media for this purpose, as it has been proposed that they can be manipulated in a way to achieve long-lived optical memories (Ros et al., 2023).

On the other hand, in atom interferometry, all the atoms contribute to the measurement signal, and the quantum shot noise (QSN) limit scales with the square root of the number of atoms. Therefore, in order to approach the QSN limit observed in atom interferometry with stored light interferometry, one should reach the regime where the number of stored photons approaches the number of atoms in the cloud. So far, most of the analysis of EIT and EIT-based QMs relies on the so-called "weak probe" regime, where $\Omega_P/\Omega_C \ll 1$ and the number of photons in the probe field is much smaller than the number atoms interacting with the optical fields, that is, $n_{photons} \ll n_{atoms}$ (Fleischhauer and Lukin, 2000; Fleischhauer et al., 2005; Rastogi et al., 2019). In these conditions, classical optical pulses can be coherently stored in ultra-cold atoms for seconds (Zhang et al., 2009; Dudin et al., 2013). Some works have investigated EIT in the strong probe field regime, in a ladder scheme (Wielandy and Gaeta, 1998; Dutton and Hau, 2004) and Λ-scheme in Bose–Einstein condensates (Pandey and Natarajan, 2008); based on these studies, one can claim that EIT can indeed be observed in this regime, and in specific conditions, light storage will be coherent. Nonetheless, a complete analysis of EIT in cold atom clouds with $n_{photons} \sim n_{atoms}$, which could address all the concerns related to our proposal, is yet to be presented. More specifically, such an analysis should answer how the efficiency of the memory would be affected in this regime or whether the phase information would be also stored and retrieved coherently. The latter is of utmost importance since the success of motion sensing using QMs relies on full coherent control over the phase of the probe field, a feature which has been shown in the weak field regime.

6. Conclusion

Here, we have presented a scheme for motion sensing by applying optical memories in both warm vapors and cold atoms. As the storage time of an optical pulse extensively exceeds the delay time in EIT, the proposed method can considerably enhance the sensitivity of recent velocimetry measurements based on the EIT-enhanced light-dragging effect. Moreover, the same principle is used to suggest a new method for measuring local gravitational acceleration, which would test the limits on the number of photons that can be coherently stored and retrieved in a cold atomic cloud. Lastly, for the case of motion sensing using warm vapor cells, we have presented a detailed description of a suitable experimental setup to test the scheme. By realizing the idea put forward, the limits of QMs would be investigated for applications in quantum sensing and can open new paths in employing these systems in areas other than quantum communications.

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Competing interests. None.

Ethics statement. This research did not require any ethical approval as it does not involve any study on animals and/or humans.

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