Demonstration of high performance on broadband storage with Electromagnetically-induced-transparency-based cold atom memory

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Quantum information processing relies on an excellent performance of memory control, including processing broadband memory. The atomic system is one of promising way to implement memory, but it becomes hard to store information once going to broadband region due to its naively narrow linewidth (few MHz). In this work, we detailed present theoretical discussion and experimental demonstration to improve high-performance atomic broadband optical memory based on Electromagnetically-induced-transparency (EIT) protocol. The storage efficiency is realized 77% with pulse duration time 30 ns (14.7 MHz) and over 50% with pulse duration time 14 ns (31.42 MHz), of which time duration are less than caesium D1 line transition lifetime (34.89 ns). In addition, the great performance for a longer storage time of optical quantum memory also has realized with time-bandwidth-product (TBP) = 1267. This work demonstrates one of the promising ways for broadband information control in the atomic system, and it has the potential to reach even higher performance.

I. INTRODUCTION

Both quantum computing and quantum communication rely on quantum memory, which stores information and retrieves it on demand. Yet, to characterize good quantum memory, there are several criteria, including high efficiency, longer storage time, good fidelity, bandwidth, or low noises. To realize high performance quantum memory in real application, however, several different standards must be met simultaneously. In this work, we focus on broadband memory with both high efficiency and high time-bandwidth product (TBP), which represents quality of longer storage.

To date, there are many different approaches to implement quantum memory, including electromagnetically induced transparency (EIT) [6] [18] [19], gradient echo memory (GEM) [16] [17], atomic frequency combs (AFC) [11] [12], off-resonant Raman memory in cold atomic ensembles [10], atomic vapors [8], and solids [13]. Among them, off-resonant Raman memory is well-known for its high potential to implement broadband memory [8] [10]. With enough optical depth and strong write/read pulse, gigahertz-level bandwidth memory has been demonstrated in warm atomic vapor [5]. Yet, while high optical depth (above 1000) is required for good efficiency, it is typically implemented in warm atomic vapor, which also enlarges decoherence rate and thus suppresses longer timed storage performance. In cold atomic system, on the other hand, decoherence rate is relatively small. However, optical depth is also typically small and thus hard for implementation of broadband memory.

Another potential candidate is EIT-based memory. By slow light scheme, we could easily control speed of spin-wave and thus store information into ground state coherence inside atoms. Also, associated with cold atomic ensembles, decoherence rate can be largely reduced. However, due to its interference feature, transparency window is typically limited to less than transition linewidth (Γ), and therefore it is not instinctive to implement broadband memory with EIT scheme. However, with proper selection among parameters space, we find that performing high efficiency is possible via EIT scheme.

In this paper, we (1) discuss the feasibility and requirements of using Electromagnetically-induced-transparency-based (EIT-based) approach in cold atomic system, and (2) present its performance in our system. Roughly 77% storage efficiency on pulse with duration 30 ns and above 50% on pulse with duration 14 ns are demonstrated, and we’ve reached time-bandwidth product (TBP) = 1267, defined as the ratio of the storage time at 50% storage efficiency to the FWHM input pulse duration (T_p), which is another crucial figure of merit we used to diagnosis longer times storage performance.

II. REQUIREMENTS FOR HIGH EFFICIENCY

In three-level Λ system, the storage efficiency can be derived from solving the dynamics of atomic excitation and atom-light interaction. Such dynamics can be well-described by optical-Bloch equations,

\[ \partial_t \sigma_{31} = -\frac{\Gamma}{2} \sigma_{31} + \frac{i}{2} \Omega_{21} \sigma_{21} + \frac{i}{2} \Omega_s \sigma_{31} \]

\[ \partial_t \sigma_{21} = -\gamma_{21} \sigma_{21} + \frac{i}{2} \Omega_c \sigma_{31} \]

\[ \frac{1}{c} (\partial_t + \partial_z) \Omega_c = i \eta \sigma_{31} \]

Where σ_{i,j} denotes atomic coherence between i, j states, and the correspondence energy level refers to Fig.2(a). \( \gamma_{21} \) denotes ground-state decoherence; \( \gamma_{31} \) denotes decoherence rate, \( \Omega_{c(p)} \) denotes Rabi frequency of coupling light (probe light). \( \eta \equiv \frac{D_i}{2L} \), where D denotes optical depth.
and $L$ denotes length of ensemble. We restrict our case to the condition both probe beam and coupling beam are on resonance, which produces the best efficiency [1].

By solving Eq.1, the behavior of output pulse can be predicted. When the input is simply continuous wave, the efficiency can reach almost unity. Yet, in the case of short-pulse signal, especially full width at half maximum (FWHM) in time domain shorter than transition lifetime, since its profile in frequency domain extends broadly and easily goes beyond transparency window, efficiency is therefore severely suppressed. Under the assumption that $\Omega_c$ is large enough to assure the slow light propagation feature of probe beam inside atomic ensembles, the efficiency of pulse input is determined by FWHM of input pulse in time domain (denotes as $T_p$) and the experimental parameters mentioned above. In such condition, the general relationship can be described as

$$T = \frac{e^{-2\gamma_2 T_d}}{\sqrt{1 + \frac{82ln2\gamma_2 T_d}{\pi D}}}$$

where $T_d$ denotes time delay due to slow light, and we define $\xi \equiv \frac{T_d}{T_p}$ [1].

Based on Eq.2, higher $D$ favors higher efficiency. Also, by adjusting magnetic field to be almost zero, typically we can reach $\gamma_2$ about $10^{-4}$ level, meaning numerator in Eq.2 is almost unity. Thus, main factors affecting efficiency is denominator. From Eq.2, it’s easy to see that small $\xi$ favors higher efficiency. However, we have to ensure almost whole part of input signal is stored into atomic ensembles, and thus typically $\xi$ has to be larger than some certain value [1] [2]. Usually, we search $\xi \approx 2 \sim 3$ to optimize both efficiency and profile fidelity of stored light.

### A. Maintaining Best Time Delay

Based on previous argument, the efficiency of stored light is mainly determined by $\xi$. For extremely short pulse, however, if we have to remain higher efficiency by letting $\xi$ remain the best value, denoted as $\xi_{best}$ ($\approx 2 \sim 3$), we have to enlarge $\Omega_c$ so that $T_d$ can be shorter, since now time duration ($T_p$) decreases, i.e.

$$T_d = \xi_{best} T_p = \frac{D \Gamma}{\Omega_c \xi_{best}}$$

$$\Omega_c = \left(\frac{D \Gamma}{\xi_{best} T_p}\right)^2$$

The required coupling power goes higher to remain $\xi_{best}$ in short pulse regime in order to achieve high efficiency.

### B. Distortion

On the other hand, broadband feature triggers another issue. Signal becomes much easier to be distorted if pulse duration time is short, even though in the same $D$ and $\xi$. The reason is that its profile in frequency domain spreads out of EIT transparency window, coupling to nonlinear region and triggering dispersion behavior, and then it goes out of slow light region and behavior cannot be well described by Eq.2 anymore. If the pulse profile goes much broader and even couples to region out of two-level absorption spectrum, the distortion can be much more severe. For example, single pulse may split into multiple pulses and oscillate in time domain [3]. In Fig.1a, we numerically demonstrate cases with different $\Omega_c$. When coupling isn’t large enough to protect input bandwidth, distortion occurs and the shape of slow light splits into multiple pulse. In such case, distortion hinders application of high performance optical storage.

To quantify required $\Omega_c$ in order to avoid such distortion, we have to consider the ratio of coupling Rabi frequency ($\Omega_c$) and bandwidth of input pulse in frequency domain, $B_{FWHM} = \frac{0.44}{T_p}$ [3]. To be immune to distortion, almost all of signal profile in frequency domain needs to be located inside transparency window, i.e., $\Omega_c/(2\pi B_{FWHM})$ is large enough [2] [3]. Quantitatively, this ratio should be larger than 4, so that the whole signal can be treated as slow light and enter into EIT protocol region [2] [3]. In such case, wave shape of signal can propagate without severe distortion.

$$\frac{\Omega_c}{2\pi B_{FWHM}} = \frac{\Omega_c T_p}{2\pi \times 0.44} \geq 4$$

$$\Omega_c \geq \frac{1.76 \times 2\pi}{T_p}$$

Notice that to go to region immune to distortion, $\Omega_c$ must be bigger than $\frac{1.76 \times 2\pi}{T_p}$ for given $T_p$. Only in that case, dynamics between atoms and light can be treated as propagation of slow light, and thus Eq.2 holds. Once entering into slow light region, Eq.3 can be derived, and thus we reach the conclusion that $\Omega_c$ should be tuned to remain $\xi_{best}$, which is roughly between $2 \sim 3$, based on experimental results.

### subsectionHigh-Performance Region

Based on arguments above, we must let two conditions (Eq.3 and Eq.4) simultaneously hold in order to implement broadband EIT-based memory with best performance, which brings us to define this condition as high-performance region.

In Fig.1b, we plot required $\Omega_c$ to reach high efficiency without distortion. Shadowed area represents condition that Eq.4 dose not hold, meaning that distortion happens. The other three colors denotes different $D$, and colored area denotes condition that Eq.3 holds for $\xi = \frac{2}{\sim 3}$, respectively. Since $\xi_{best}$ is roughly between this interval ($2 \sim 3$), the optimized point locates inside this region. The area inside this colored region and not in the shadowed area, meaning both Eq.2 and Eq.3 holds, is high-performance region for given optical depth, $D$.

Let’s now consider when duration time of input signal goes shorter. If $D$ is fixed, when changing to smaller $T_p$,....
However, since and find out another suitable Ω means the shortest pulse certain can reach. In Fig.1c and Fig.1d, we shows efficiency against different OD and Rabi Frequency of coupling beam. The pink dash light denotes Ωc equals 4BFWHM, respectively. The purple dash line denotes the requirement for ξ = 2.25. Diamond Marker denotes efficiency reaches 80%, 90%, 95%, respectively. Corresponding Rabi frequency of coupling is much higher in \( T_p = 30\) ns than one in \( T_p = 200\) ns.

It basically we are tracing leftward along one colored branch and find out another suitable Ωc to match \( \xi_{\text{best}} \), i.e. Eq.2. However, since \( T_p \) in Eq.4 goes with power of \(-1/2\) and in Eq.3 only goes with power of \(-1/2\), there must be an intersection when colored branch sinks into shadowed area when keep decreasing \( T_p \), which means distortion might appear. When \( T_p \) goes below that intersection point, retrieval signal cannot be immune to distortion anymore if \( D \) remains the same. At that point, we’ve reached shortest \( T_p \) that such \( D \) can perform storage. Thus, to go further into shorter pulse storage, increasing \( D \) is necessary, meaning transfer into another higher colored branches in Fig.1b. That is to say, since the intersection goes leftward when \( D \) goes larger, larger \( D \) has more potential to store shorter pulses. However, in that case, higher Ωc is required, and such more and more strict requirements on parameters space for shorter pulse is also the reason why broadband EIT-based memory is hard to implement.

In Fig.1b, to store pulse shorter than natural lifetime in our atomic system (34.89 ns), \( \Omega_c \approx 13\Gamma \) and \( D = 400 \) is needed. To go to broader region GHz-level short pulse, \( \Omega_c \approx 500\Gamma \) is needed.

C. Theoretical simulation and Conclusion

To attain more comprehensive picture, we do simulation across whole parameters space. In Fig.1c and Fig.1d, we simulate stored light for different \( D \) and Rabi frequency of coupling light \( \Omega_c \), in two different \( T_p \). We can observe that it’s required to go to both high \( D \) and \( \Omega_c \) to attain high efficiency, and the requirement is also more strict for shorter input pulse. In real experiments, we want to follow the purple curve in Fig.1d, meaning remaining \( \xi_{\text{best}} \approx 2.25 \), to reach higher efficiency, and the requirement for both \( D \) and \( \Omega_c \) would be higher in shorter input pulse.

To sum up the discussion above, there’s no naturally physics limitation on performing storage in EIT-based cold atomic system. However, when going into shorter pulse region (broadband regime), both higher \( D \) and \( \Omega_c \) must be prepared. In the following, we experimentally demonstrate our EIT-based broadband optical memory based on Cesium atomic system.

III. EXPERIMENTAL PROCEDURE

In our experiment, we utilize a magneto-optical trap (MOT) via cesium to implement EIT-based optical memory. We use trapping beams to drive \( |F = 4\rangle \rightarrow |F' = 5\rangle \) transition of the \( D_2 \) line for cooling down atoms temperature and repumper beams to drive \( |F = 3\rangle \rightarrow |F' = 4\rangle \) transition of the \( D_2 \) line for repumping atoms back into cooling process. In order to implement broadband high efficiency optical memory, ultrahigh optical depth is needed. Therefore, We utilize a two-dimension MOT to produce cigar-shape atomic cloud, which can efficiently increase optical depth in certain axis. To achieve this, we perform temporal dark MOT to compress atomic cloud in one of transverse direction after standard MOT procedure. In experiment, another depumping beam is sent to the atomic ensemble, driving \( |F = 4\rangle \rightarrow |F' = 4\rangle \) transition of the \( D_2 \) line while ramping up magnetic field at the same time. By doing so, number density is largely enhanced along z axis, which is defined as the direction probe beam and control beam propagate. To compress with even larger extent, we also add another pair of trapping beams in one of transverse direction, which enhances dipole force in that direction and therefore makes atomic number density in z axis higher. The visualized setup is demonstrated in Fig.2a. Besides from dark MOT, depumping beam also plays the role to pump atomic population back from \( |F = 4\rangle \) into \( |F = 3\rangle \) in order to do following EIT procedures.
When performing EIT storage, probe beam drives $|F = 3 \rangle \rightarrow |F' = 4 \rangle$ transition of $D_1$ line, and coupling beam drives $|F = 4 \rangle \rightarrow |F' = 4 \rangle$ transition of $D_1$ line. The reason using $D_1$ transition is that such a choice could avoid photon switching effect and therefore possesses greater potential to reduce ground-state decoherence [1]. Also, both probe beam and coupling beam drive in $\sigma^+$ channel, and the reason is in the following. Larger Clebsch-Gordan coefficients of transition favor greater optical depth, and thus we intend to prepare atom in $|F = 3, m = 3 \rangle$ Zeeman substate and drive in $\sigma^+$ transition. Based on feature of Clebsch-Gordan coefficients, such a transition yields the largest Clebsch-Gordan coefficient and thus create greater optical depth. The relative energy levels are demonstrated in Fig.2b. It should be noticed that in order to prepare atomic population into $|F = 3, m = 3 \rangle$ Zeeman substate, we send additional optical pumping beam to ensemble, gathering atoms into such desired state just before EIT measurements. By pumping population into single Zeeman substate also makes storage performance less sensitive to stray magnetic field [2] [1], which is desirable for long-time storage. By methods mentioned above, we’ve reached $D \approx 2000$ in cold atomic ensembles in previous work [3]. Also, many efforts are made to reach higher efficiency, such as decreasing $\gamma_{21}$ by adjusting magnetic field or adjusting light path of both probe beam and coupling beam [1].

Our detailed setup is plotted in Fig.2c. Initially, our probe beam laser source doubly passes one acousto-optic modulator (denoted as AOM1) to adjust probe beam frequency. It is later sent to another acousto-optic modulator (denoted as AOM2) to create $160\mu s$ square pulse. Probe beam is then coupled into fiber electro-optic modulator, which can fast create short pulse with duration larger than $10\, \text{ns}$. Shorter than $10\, \text{ns}$, some distortion will occur. The purpose of adding AOM2 to create square pulse is to avoid light leakage when doing storage. After preparation, probe beam is then sent to atomic system module and coupled with coupling beam with 50 : 50 beam splitter. After coupling together, both of them are sent into cold atomic ensembles. Before coming into MOT cell, the probe beam is focused by a lens (L1 in Fig.2c) to an intensity $e^{-2}$ diameter of $\sim 100\, \mu \text{m}$ around the atomic clouds while the control beam is collimated by the same lens (L1) with a diameter of $\sim 240\, \text{mm}$. After going out from MOT cell, coupling beam is focused by the other lens (L2) and be blocked by black dot. Probe beam, on the other hand, is collimated by the such a lens (L2) and then coupled into fiber before passing through three irides and a etalon, which makes sure only probe beam is detected. Such signal is then detected by a photomultiplier tube (Hamamatsu R636-10). The visualized setup is plotted in Fig.2c and the more detailed information about our atomic setup can be referred to [4].

FIG. 2: In Fig.2a four pairs of arrows represent four pairs of counterpropagating trapping beams. One of the four pairs in x direction is the additional pair used to compress atomic ensemble into cigar shape, denoted as larger arrows in the figure. Solid yellow arrow means probe beam, while the other translucent arrow means coupling beam, and it is overlapped with probe beam; Fig. 2b shows energy levels of our EIT setup. In Fig.2c both probe preparation and atomic setup are plotted. AOM denotes acousto-optic modulator; BS denotes Beam Splitter. FE denotes fiber electro-optic modulator; RF denotes Radio frequency signals; PMT denotes photomultiplier tube; M denotes mirror; L denotes lens; WPs denotes multiple waveplates; FC denotes fiber coupler; Port 1 is transmitted by polarized-maintaining fiber. The preparation of coupling beams and cooling beams are not plotted in Fig.2c.

IV. RESULTS AND DISCUSSION

In the following, we experimentally demonstrate our broadband EIT-based optical memory via cold atomic system. The following subsections are arranged in the described way: We firstly present the range of parameters space that our system possesses, and by manipulate parameters within such a range we are able to reach high performance storage for input pulse with duration time even smaller than transition lifetime. Later, we present our storage with different input bandwidths, and we are able to implement high performance when tuning to different bandwidths. Yet, based on some technical issues, the efficiency drops at the case of very large bandwidth. Last, we will present our results of light storage for longer times. Since it is stored in cold atomic ensembles, which
possess smaller ground-state decoherence, longer time storage can be realized.

A. Demonstration of high efficiency storage light

Here, we present large range of parameters space in our system, and by searching for the proper parameters we can reach storage efficiency higher than 77\% in our EIT-based optical memory for broadband input signal \( T_p = 30\text{ns}, \text{or } B_{FWHM} \approx 14.7\text{MHz} \). In Fig.3 we adjust different \( D \) (from 0 \( \sim \) 528) by tuning different trapping beam power, and then we search for suitable \( \Omega_c \) to optimize efficiency. The corresponding \( \xi_{\text{best}} \) is roughly 2.25 \footnote{1,3}. Experimental parameters chosen are plotted in Fig.3a and efficiency of each case is demonstrated in Fig.3b. In the case \( D = 528 \) and \( \Omega_c \approx 16.4\Gamma \), we’ve reached the highest efficiency, 77.7\% (average of multiple measurements), in our system.

In Fig.3c raw data are demonstrated. We use Gaussian fitting to determine efficiency. Yet, to avoid mistakenly calculating in little amount of probe leakage even though fiber EOM is switched off, we subtract area of Gaussian pulse by offset determined by input(without atom). i.e.

\[
A_{\text{storage}} = A_{\text{fitted from storage}} - of f set_{\text{fitted from input}}*\Delta_{\text{AOM}}
\]

where \( A_{\text{fitted from storage}} \) denotes area of pulse calculated by Gaussian fitting; \( of f set_{\text{fitted from input}} \) denotes small offset fitted from input light data (without atoms); \( \Delta_{\text{AOM}} \) denotes period AOM2 is switched on. In our experiment, it is 160\µs.

B. Discussion of different bandwidth

In this subsection, we demonstrate our memory performance along different bandwidths, i.e. different duration time, \( T_p \).

Since we have demonstrated 77\% storage efficiency for \( T_p = 30\text{ns} \) already, we now adjust to different input duration times and try to present such high efficiency along different input cases. To achieve the same high storage efficiency, required \( \Omega_c \) will be lower once going into larger \( T_p \), and therefore for \( T_p > 30\text{ns} \) it is easier to perform over 77\% efficiency. Yet, toward the shorter \( T_p \) region, requirements for both \( \Omega_c \) and \( D \) rise fast, which can be seen from Fig.1b and discussion in previous section. It means that it is increasingly tougher to maintain such efficiency in shorter \( T_p \) case.

In Fig.4a we present the storage efficiency we reach, and Fig.4b shows chosen \( \Omega_c \) for each case. From the large \( T_p \) to shorter \( T_p \), the efficiency maintains at over 77\% level but suddenly drops when \( T_p \) goes shorter than 30\text{ns}. This sudden drop arises purely because the largest parameters that our system can yield are not large enough to satisfy requirements for maintaining the efficiency at same high level, 77\%, when entering into shorter pulse region. To solve such problem, increasing both \( D \) and \( \Omega_c \) is necessary. However, in our system, though it’s possible to keep increasing \( D \), coupling intensity is hard to increase in our recent setup. Therefore, the experimental \( \Omega_c \) is limited by the maximum value \( \approx 16.5\Gamma \). Such technical constraints among parameters space hinder us to maintain high efficiency level along shorter \( T_p \) cases.

However, in such case, we can still get over 50\% efficiency for \( T_p = 14\text{ns} \), or say \( B_{FWHM} = 31.42\text{MHz} \approx 6.89\Gamma \). In Fig.4c we present our raw data. For the slow light curve, some small fraction of signal distributed after main Gaussian peak can be observed, which is distortion due to limited coupling Rabi frequency. In the more extreme case, if \( \Omega_c \) decreases, distortion appears more obviously and multiple peaks oscillate after main peak, as we show in Fig.4d. Such oscillation occurs when bandwidth broadly distributes beyond two absorption peaks, and there is another protocol, ATS memory, using such effect to store broadband signal \footnote{3,2}.
FIG. 4: In Fig. 4a, solid curve denotes required $\Omega_c$ (for $\xi_{best} \approx 2.25$ at the $D = 528$) and experimental $\Omega_c$. For $T_p < 30\,\text{ns}$, the maximum $\Omega_c$ that our system can yield cannot meet the requirements. In Fig. 4b, we present storage efficiency in different input duration times. In Fig. 4c, we demo one of raw data of $T_p = 14\,\text{ns}$ and the storage efficiency is 54.8%. In Fig. 4d, we show one of raw data to demonstrate occurrence of distortion when $\Omega_c$ is not large enough. The input duration time is also 14\,\text{ns}, and $D = 185$, $\Omega_c = 8.3\Gamma$.

C. Storage with longer time

In this part, we discuss more about storage performance for longer times. In order to do application on information storage, storage efficiency for longer time must be discussed, and cold atomic ensembles, which is able to reduce $\gamma_{21}$ to smaller level compared with warm vapor, has more potential to apply longer time storage. Here, we use another crucial figure of merit, TBP, defined as the ratio of the storage time at 50% storage efficiency to the FWHM input pulse duration ($T_p$), to diagnosis our performance on long times storage \cite{1}. In this subsection, we demonstrate TBP to be 1267 for our broadband EIT-based optical system, even a little bit higher than that of previous work (TBP$=1200$), which was conducted on relatively narrow bandwidth ($T_p = 200\,\text{ns}$). In Fig. 5, we demonstrate storage efficiency of our EIT-based optical memory storing $T_p = 30\,\text{ns}$ signal from 200\,\text{ns} to 70\,\mu\text{s}. To improve TBP, adjusting magnetic field to zero plays a critical role. Therefore, we also use microwave to make sure magnetic field approaches zero, and the detailed procedure is in the following. We did not apply optical pumping intentionally so that atomic population is equally distributed among all sub-Zeeman states, i.e. from $|F = 3, m = -3\rangle$ to $|F = 3, m = 3\rangle$. In the next, we apply microwave to drive atomic population from $|F = 3\rangle$ to $|F = 4\rangle$ for 50\,$\mu\text{s}$, and then turn MOT beam on to resonance for 70\,$\mu\text{s}$ and collect florescence by CCD camera. By scanning microwave through 9.192 GHz, some florescence peaks are observed. If magnetic field exists, florescence peak is splitted into several peaks due to Zeeman effects, and the number of splitted peaks depends on direction of magnetic field. Once magnetic field is turned to zero, all peaks combine together and only one main peak can be observed. By this method, we scan magnetic field of $x, y, z$ direction and search for the point that non magnetic field exists.

Yet, even though making sure that magnetic field approaches zero, the absolute storing time for storage efficiency large than 50%, defined as $T_{s,50\%}$, is only 38\,$\mu\text{s}$, which is much less than $T_{s,50\%}$ in our previous work (larger than 200\,$\mu\text{s}$). Theoretically, based on storing model considering ground state decoherence rate and stray magnetic field \cite{3}, $T_{s,50\%}$ shouldn’t change even though bandwidth of probe input becomes extremely large. Therefore, the reason that broadband input possesses larger ground state decoherence rate still remains mystery, and at least we cannot make great improvement by adjusting magnetic field to zero.

V. CONCLUSIONS AND OUTLOOK

In summary, requirements for high performance in EIT-based memory has been theoretically discussed, and both large $D$ as well as $\Omega_c$ are necessary to reach high storage efficiency without severe distortion. We later also experimentally present our EIT-based broadband optical
memory, with efficiency 77% for 30 ns pulse and over 50% for 14 ns pulse. Also, as for storage, we’ve reached high time-bandwidth product (TBP), 1267. In our atomic system, some technical problems hinder us to explore region with larger broadband. Yet, good performance in storage efficiency, long storage times even when duration time is shorter than lifetime present promising way to implement broadband information storage in quantum information science, and it has potential to reach higher performance once some technical problems are solved.

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