Storage and Retrieval of Multimode Transverse Images in Hot Atomic Rubidium Vapor

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We report on the experimental realization of the storage of images in a hot vapor of Rubidium atoms. The images are stored in and retrieved from the long-lived ground state atomic coherences. We show that an image impressed onto a 500 ns pulse can be stored and retrieved up to 30 μs later. The image storage is made robust to diffusion by storing the Fourier transform of the image.

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“Stopped light” usually refers to the interconversion of electromagnetic fields into long-lived atomic coherences. It allows for the recording of coherent signals for later retrieval even at very low light levels. The initial work by Liu et al. [1] and Phillips et al. [2] stimulated additional research with a recent demonstration of storage times in excess of 1 s [3]. Stopped light may be useful for applications in remote sensing, image processing, and quantum information.

Typically, the pulses used in stopped light experiments are several kilometers long in free space. However, the stopped light medium usually ranges from a few tens of microns up to several centimeters, so slow light is first used to spatially compress the optical pulses inside the medium. Slow light is achieved when a steep linear dispersion can be obtained in a medium, leading to a large group index of refraction. Slow light is first used to image the object onto the camera as well as place the Fourier plane at the cell. It consists of two lenses, $L_1$ and $L_2$, each of focal length $f = 500$ mm separated by a distance $2f$. The object is placed at the front focal plane of $L_1$ and the image is obtained at the back focal plane of $L_2$. The vapor cell is placed at the back focal plane of $L_1$ (the Fourier plane). The diameter of the cell is 1 cm and the transverse diameter of the signal beam is chosen such that the profile of Fourier image fits in the cell. The pump beam is orthogonally polarized to the signal to filter out the pump. In addition to polarization filtering, we also performed a temporal filtering correlation measurement using a 100 MHz detector (3 dB roll off). A 25 μm slit is placed in the focal plane and a bucket detector is placed behind the slit. The position of the slit is scanned in the image plane and the temporal intensity profile of the retrieved light pulse hitting the bucket detector is recorded on a 1.5 GHz oscilloscope.

Our slow light scheme is based on a combination of EIT and FWM in a $\Lambda$ system which consists of two lower energy levels coupled to a common higher energy level of the atom by two electromagnetic fields. The relevant energy levels of $^{85}$Rb are shown in Fig. 1(b). To obtain a highly transparent region which also exhibits steep dispersion, the pump and signal lasers are detuned several hundred MHz from the zero velocity class in a Doppler broadened vapor. The signal experiences both FWM gain and EIT when its frequency is tuned to the two-photon Raman resonance. As a note, optical alignment, buffer gas pressures, laser detunings, etc., all affect the transmission and dispersion. The rapid change in the transmission profile near Raman resonance leads to steep dispersion and...
Figure 2 (color online). CCD camera capture of the signal intensity profile at the object plane and at the vapor cell (Fourier plane).

Figure 3 shows the input image (a), as well as the retrieved (b) and calculated (c) image profiles for several storage times. The theory plots are generated by using Eq. (4) to propagate the measured input image shown in Fig. 3(a). The object used is an amplitude mask containing a 5 bar test pattern. We note that the image contrast remains high even for the longer storage times, even though the wings of the image decay faster than the central part, as predicted by diffusion theory. The physical mechanism responsible for preserving the image can be understood in terms of the phase distribution of the stored optical wavefront and the diffusion of the atoms (shown graphically in Fig. 4). Each atom in the field acquires the local coherence set by the signal and pump fields. As the atoms diffuse in the Fourier plane, atoms of opposite phase tend to destructively interfere preserving the high contrast. This is similar to the topological stability of stored Laguerre-Gauss beams as demonstrated by Pugatch et al. and in good agreement with the theoretical predictions by Zhao et al.

We adopt the diffusion model of Pugatch et al. to simulate image diffusion in the Fourier plane. We first determine the Fourier transform of the field in the back focal plane of $L_1$. Let $E_o$ be the field at the object plane which is also the front focal plane of a spherical lens of focal length $f$. At the back focal plane of the lens, the field $E_f$ is given by the Fourier transform of the field in the object plane:

$$E_f = F(E_o) = \frac{1}{\sqrt{2\pi f}} \int_{-\infty}^{\infty} E_o \exp\left(-i \frac{2\pi}{\lambda f} \xi u\right) d\xi,$$  \hspace{1cm} (1)
where $T_c$ is ground state decoherence time of the coherence $\rho_{13}$, and $D$ is the diffusion coefficient of the atoms. Assuming a constant pump intensity along the transverse dimension of the cell, the only spatial dependence of the ground state coherence comes from the signal field amplitude.

Figure 4 shows the evolution of the ground state coherence under the conditions of decoherence and diffusion. The inset of the figure shows a section of plot containing zero crossover points. We see that the zeros of $\rho_{13}$ are unchanged, though the amplitude on either side of zero crossovers decreases with time. As the atoms with positive and negative phases have equal probability of reaching the zero crossover point, the retrieved fields from such atoms at those points tend to destructively interfere, maintaining a zero in the field amplitude. At other points, the same interference process results in a decrease in amplitude while maintaining the field profile.

The field at the image plane, $E_i$, is recovered by inserting Eq. (1) into the diffusion equation [Eq. (2)] and taking another Fourier transform, which upon integration gives

$$\frac{\partial}{\partial t} E_i(x, t) = -\left(\frac{1}{T_d} + \frac{1}{T_c}\right) E_i(x, t),$$  \hspace{1cm} (3)

with a solution given by

$$E_i(x, t) = E_i(x, 0) \exp\left[-t\left(\frac{1}{T_d} + \frac{1}{T_c}\right)\right],$$  \hspace{1cm} (4)

where $T_d = \frac{\kappa^2}{(2\pi)^2 D}$ is the diffusion time constant and $x$ is the coordinate in the image plane.

We note that by integrating over the spatial coordinate $u$ at the cell from negative infinity to positive infinity we have not accounted for the finite numerical aperture of the 4f imaging system. The size of the numerical aperture in our system is set by the size of the pump beam at the cell, which has a $1/e^2$ intensity diameter of approximately...
4 mm. Since this is larger than the spatial extent of all relevant features in the Fourier transformed image (see Fig. 2), this approximation is valid. In addition, we have assumed that all modes of spatial diffusion for the prepared atoms remain within the pump beam diameter, so that higher order modes which exit from and then return to the pump beam during storage do not cause interference [23]. Since the diffusion length for the longest storage time is given by $D_t = 170 \mu m$, and the closest relevant feature in the Fourier transform of the image is farther than 500 $\mu m$ from the edge of the pump beam, this is also a reasonable assumption. As a note, we also performed numerical integration over the relevant finite dimensions of our experiment which produced negligible errors.

There are two features worth noting in Eq. (4). First, each spatial point in the image decays exponentially in time, with a time constant given by $1/T_d + 1/T_c$. This means that dark areas of the image remain dark for appreciable times compared to the temporal pulse length. Second, since $T_d$ falls off like $1/x^2$, the central portion of the image has maximum storage time. We can increase the diffusion time $T_d$ by making the image smaller or making the focal length of the imaging lens larger. In either case, the Fourier transformed spatial profile at the vapor cell would be larger, requiring a correspondingly larger pump beam diameter and vapor cell.

In summary, we have slowed and stored an arbitrary transverse image in a hot atomic vapor, and shown that the retrieved image is robust to atomic diffusion. This remarkable ability allows the coherent storage of spatial information even in Doppler broadened media with large diffusion constants.

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Note added in proof.—As a note, we have recently become aware of image storage in a similar system [24].


