Quantum Information Storage with Slow and Stopped Light

Joseph A. Yasi*

Department of Physics, University of Illinois at Urbana-Champaign

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Abstract

This essay describes the phenomena where the group velocity of light is reduced to ultraslow speeds, and even stopped in atomic gases. The coherent coupling of photons to atomic spin excitations in the gases through Electromagnetically Induced Transparency (EIT) is discussed, and experimental observation is presented as evidence of the phenomena with specific focus on the emergence of excited states in the material for quantum infomation storage and processing.

*Electronic address: yasi@uiuc.edu

I. INTRODUCTION AND BACKGROUND

In 1982, R. P. Feynman suggested building computational devices using the principles of quantum mechanics due to the inherent difficulties of simulation quantum systems on classical computers.[1] Following with Feynman's idea, David Deutsch sought to describe a device that could simulate an arbitrary physical system in 1985.[1] This led to the notion of a Universal Quantum Computer which could simulate arbitrary quantum mechanical systems.

Since these ideas were first presented, a large subfield of physics has developed devoted to their realization. Tremendous progress has been made in this field in the past two decades, but the field is still a long way from developing a commercially scalable system capable of arbitrary computations. Many physical and technical challenges are still present, and it is likely that the physical device that will eventually become the future scalable quantum computer currently is unknown.[2]

Two areas of development necessary for the achievement of this goal are the development of quantum communication and quantum information storage systems. Photons are the logical choice of physical system for quantum communication due to their ability to travel long distances with little decoherence.[2] However, since photons always travel at the speed of light, storage of quantum information encoded with photons is difficult. Current methods use a specially aligned cylindrical cavity, or pass the photons through kilometers of fiber optics to introduce a delay. Unfortunately, these techniques can only introduce a finite delay on the arrival of the photons, leaving the ultimate goal of storing the information unattained.

The logical choice for storage of quantum information is a cold atomic gas.[2] Interactions between atoms are weak in a cold atomic gas allowing for long storage times of quantum information without decoherence. However, the use of an atomic gas for communication is impractical since the gas cannot be transported quickly. Thus, the obvious technical challenge involves coherently transfering information from photons used for communication to an atomic gas for storage as well as the reverse of this process.

This paper will focus on recent experimental[3–6] and theoretical[7, 8] advances in the field of slow and stopped light which allow for the coupling of information stored in a photon field to atomic excitations in an atomic gas. The most common technique for accomplishing this is a quantum interference effect called electromagnetically induced transparency (EIT). Using this technique, experimenters have been able to slow the group velocity of light down to 17 m/s in a BEC[6] and in some cases, temporarily stop the propagation of light altogether[3–5], nondestructively continuing propagation at a later time. There is even promising theoretical progress in techniques for the manipulation of this information while it is stored in the atomic gas[8].

II. METHODS

A. Electromagnetically Induced Transparency

Electromagnetically induced transparency (EIT) is commonly used to slow the group velocity of light to a fraction of the vacuum speed of light in materials such as atomic gases. EIT is a quantum interference technique which renders a normally opaque material transparent during the application of a coupling electromagnetic field. This technique was discovered by Geraldo Alzetta at the University of Pisa in 1976.[9] The physical effect causing

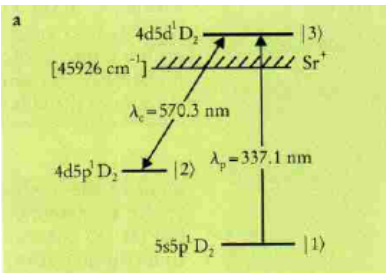

FIG. 1: A 3-level system in Strontium vapor with coupling wavelength λ_c and probe wavelength λ_p.[9]

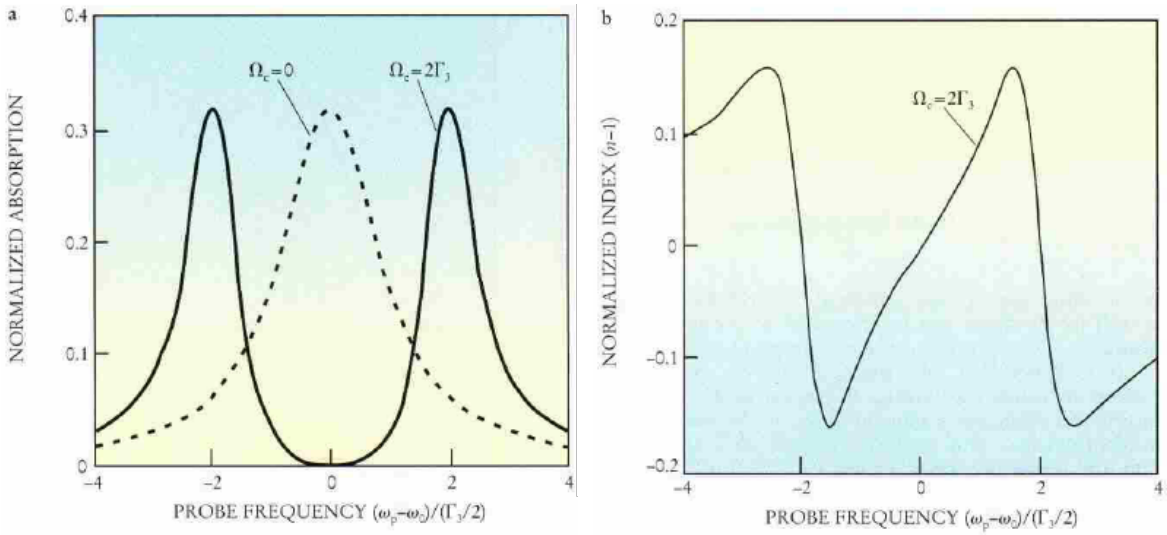

FIG. 2: a. Absorption spectrum as a function of the probe detuning with and without the coupling laser applied. b. Refractive index as a function of the probe detuning from resonance. Ω_c is the Rabi frequency of the coupling field. Γ_3 is the decay rate of the excited state.[9]

the transparency is called coherent population trapping.

To understand the process of coherent population trapping, consider an atomic gas of Strontium described by the three-level system depicted in Fig. 1 prepared in the ground state $|1\rangle$. This gas is normally opaque to unescorted light at wavelength λ_p because the application of light at this wavelength causes a transition to $|3\rangle$, and the light is absorbed. This causes the absorption peak depicted as the dashed curve in Fig. 2a.

This material can be made highly transparent through the use of EIT. By applying a coupling field at wavelength λ_c, the transition wavelength for $|2\rangle \rightarrow |3\rangle$, flourence from $|3\rangle$ is strongly reduced.[9] By applying the coupling field, the gas is driven into a coherent super position of states $|1\rangle$ and $|2\rangle$ with $|3\rangle$ empty causing coherent population trapping. Application of this coupling field causes the aborption peak in the material is split as in the solid line in Fig. 2a. Now, when a probe field of wavelength λ_p is applied, it passes through the gas.

Another interesting aspect of the EIT is depicted in Fig 2b. When the coupling field is applied, the refractive index of the material becomes unity and sharply linear about the $|1\rangle \rightarrow |3\rangle$ transition frequency. By controlling the slope of the index of refraction curve, the

group velocity through the material can be controlled.

$$v_g(\omega) = \frac{d\omega}{dk} = \frac{c}{n(\omega) + \omega\frac{dn}{d\omega}} \tag{1}$$

Thus, if the index of refraction curve can be made extremely steep, the group velocity of the probe signal can be reduced to speeds much smaller than the speed of light, allowing for delays of photonic signals without long cavities or fiber optics. Since the refractive index at the probe resonance frequency is unity, the probe signal is left virtually undistorted as it exits the material.

Small group velocities also mean that the signal is spatially compressed inside the material. If the size of the signal is smaller than the length of the material, EIT can be used to store the quantum signal within the material. By adiabatically turning off the coupling field after the tail of the probe signal has entered the material, the probe signal can be stored in the atomic excitations of the material. This is useful for the development of quantum memory devices.

B. Dark-State Polaritons[7]

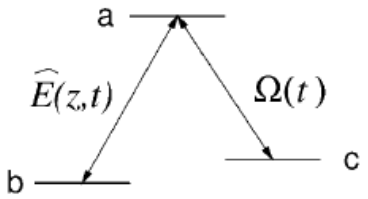

FIG. 3: A 3-level system coupled to a control field with Rabi frequency $\Omega(t)$ and a quantum probe field $\hat{E}(t)$.[7]

Theoretically, the coupling of the photonic probe field to the atomic field can be described by making a canonical transformation described in eq. 10 of [7].

$$\hat{\Psi}(z,t) = cos\theta(t)\hat{E}(z,t) - sin\theta(t)\sqrt{N}\hat{\sigma}_{bc}(z,t) \tag{2}$$

$$cos\theta(t) = \frac{\Omega(t)}{\sqrt{\Omega^2(t) + g^2N}} \tag{3}$$

$$sin\theta(t) = \frac{g\sqrt{N}}{\sqrt{\Omega^2(t) + g^2N}} \tag{4}$$

Where $\Omega(t)$ is the Rabi frequency of the classical control field, $\hat{E}(t)$ is the quantum probe field, $\hat{\sigma}_{bc}(z,t)$ is the spatially averaged atomic transition field between the two lower atomic levels, $|b\rangle$ and $|c\rangle$, g is the atom-field coupling constant, and N is the number of atoms in the quantization volume. This expression for the new quantum field is only valid if the atomic operator equations can be expanded perturbatively in the probe field, and the Rabi frequency of the control field is changed adiabatically. The equations can be treated perturbatively if the Rabi frequency of the probe field is initially small compared to the

control Rabi frequency, and the number of photon in the probe pulse is small compared to the number of atoms[7]. In the limit that the density of probe photon is small compare to the density of atoms, this new quantum field has an interesting commutation relation[7]:

$$\left[\hat{\Psi}_k, \hat{\Psi}_k^\dagger\right] = \delta_{k,k'} \tag{5}$$

The new field is bosonic, and thus represents quasiparticles known as dark-state polaritons. These states are known as dark-states because they do not mix the excited atomic state at all, and are zero modes of the interaction Hamiltonian[7]. Thus by controlling $\Omega(t)$, the mixing angle $\theta(t)$ changes causing the photonic and atomic component of the polaritons to be varied. By varying the mixing angle, the quantum probe pulse can be stored in the atomic field and retrieved later by returning $\Omega(t)$ back to the original value. This presents strong theoretical support for quantum coherence of the probe field with the atomic gas in EIT, allowing for quantum memory devices.

There is also theoretical support which would allow the manipulation of the shape of the quantum probe field when it is stored in the atomic gas[8]. By sending counter-propagating control signals into the gas after the probe pulse is stored in the atomic excitations, a small photonic component can be imparted on the polariton field without causing the signal to leave the material. The photonic component undergoes a diffusion process which causing a controllable spreading of the pulse. This could be useful for manipulation of photonic quantum signals.

III. RESULTS AND DISCUSSION

A. Slow Light in an Atomic Gas

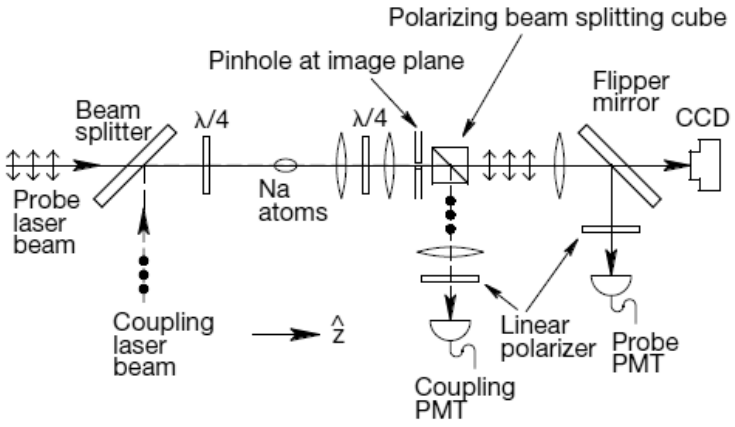

FIG. 4: An experimental set-up for EIT based optical information storage in cold sodium gas.[3]

There are many recent experiments which utilize electromagnetically induced transparency to slow the group velocity of light through atomic gases. A typical experimental set-up for achieving slow group velocities by EIT is depicted in Fig. 4. In this particular experiment, the probe and coupling field co-propagate through Sodium vapor. The coupling

beam is left circularly polarized, and the probe beam is right circularly polarized. The probe and coupling beam are then collected onto photomultiplier tubes for simulataneous monitoring of the two signals.

Using EIT in a cold ($0.9\mu K$) gas of sodium atoms, Chien Liu et al.[3] where able to observe coherent optical information storage. By switching off the coupling signal once the tail of the probe pulse has entered the gas, then switching the coupling signal back on after a delay, they were able to observe a controllable delay of the output probe pulse. They are able to achieve delays in excess of $839.3\mu s$ while maintaining the shape of the original coherent optical pulse. The transmission of the pulse is only about 10% of the orignal pulse intensity after a $839.3\mu s$ delay, but this is only half of the transmitted intensity when there is no delay between write and retrieve.

By modifying the intensity of the retrieve coupling beam relative to the intensity of the write coupling beam, they were able to modify the width and intensity of the output probe pulse. By increasing the intensity of the retrieve beam, the width of the output probe pulse is decreased, and the intensity of the output pulse is increased. If the intensity of the retrieve pulse is decreased, the width of the output probe pulse increase and the intensity decreases. They are able to get the output probe pulse's intensity to exceed the intensity of the input pulse by 40% by increasing the strength of the retrieve pulse by a factor of 20. These pulse manipulation techniques could prove useful in information retrieval.

They were also able to demonstrate partial retrieval of the output probe pulse by switching on the retrieve pulse in short bursts. Measuring the energy in the combined partially retrieved pulses to be equal to the total energy of a singly retrieved pulse. Showing that each pulse contains a piece of the atomic memory.

Though the delays and results of this technique are promising, the probe pulses stored and retrieved are weak classical fields, and quantum coherence is not demonstrated. Thus, an improved experiment is necessary if this setup is to be used as a quantum information storage device.

However, C. H. van der Wal et al. were able to demonstrate quantum coherence in the retrieval of a probe pulse stored in a gas of rubidium atoms at $\sim 85^{\circ}C$ using a Raman excitation technique similar to electromagnetically induced transparency[4]. The Rb atoms are initially prepared in the ground state ($|1\rangle$) of a three level atomic excitation system. Spontaneous Raman scattering is induced in the gas by applying an off-resonant control beam to the gas. For each Raman scattering event, there is exactly one spin flip in the atomic system, and one frequency-shifted "Stokes" photon is emitted. The atoms that spin flip are now in $|2\rangle$. By applying a retreive beam with Rabi frequency on resonance with the $|2\rangle \rightarrow |3\rangle$ transition, stimulated Raman scattering occurs, emitting a photon for each spin flip in an "anti-Stokes" field. These emitted photons are highly correlated with the photons in the Stokes field. The degree of quantum correlation is shown in Fig. 5. Notice that the spectral density of the difference of the Stokes and anti-Stokes signals drops below the photon shot noise level around 1.6MHz. This shows good quantum coherence between the two signals, and demonstrates quantum storage in an atomic gas. However, retrieval efficiencies were limited to 10-30% and they were only able to achieve a retrieval delay of $3\mu s$. This experiment was limited by improper spatial mode matching of the write and retrieve beams, and the retrieve beam power. Despite the low efficiencies and short retrieval delays, the quantum coherence shows promise in the field of quantum information storage.

Slow light propagation has also been demonstrated in Bose-Einstein Condensates of sodium atoms using electromagnetically induced transparency by L. V. Hau et al.[6]. Due

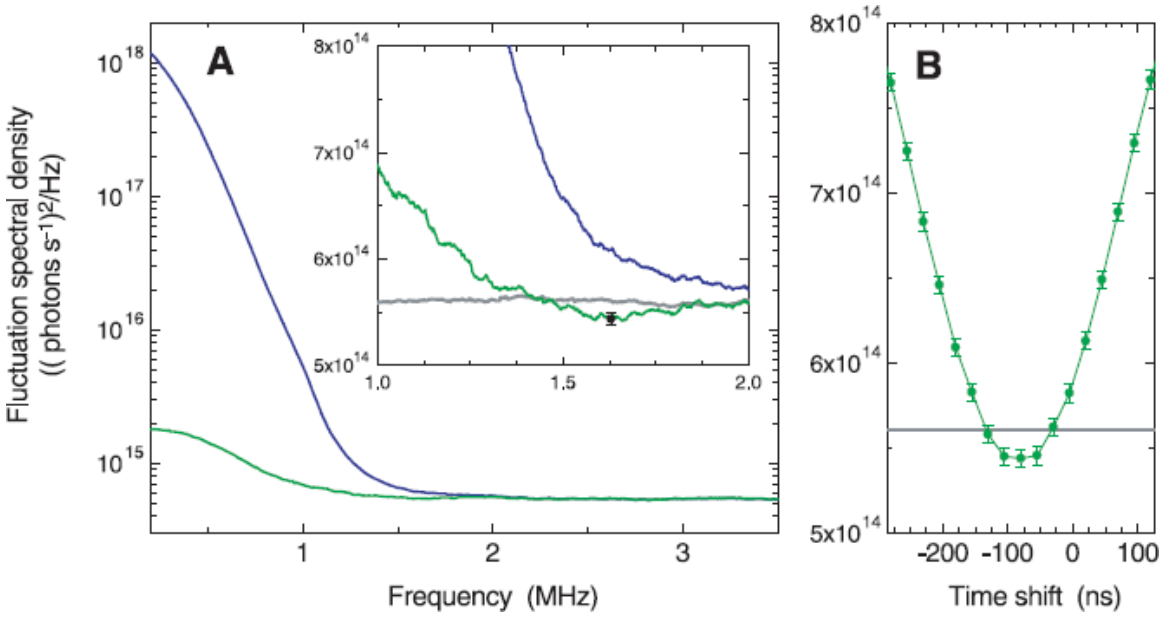

FIG. 5: Quantum correlations between the Stokes and anti-Stokes fields in a ^{87}Rb atomic memory device. (A) The blue curve shows the fluctuation spectral density of the anti-Stokes field, and the green shows the fluctuation spectral density of the time- and amplitude-compensated difference signal between the Stokes and anti-Stokes fields. The inset shows that the fluctuations in the difference signal drop below the measured photon shot noise level (gray curve). The error bars on the black point are $\pm 1\sigma$. The dip below the photon shot noise level shows nonclassical correlations. (B) This shows the fluctuation spectral density of the difference at 1.6MHz as a function of the delay parameter between the Stokes and anti-Stokes fields (green). The gray curve is the photon shot noise level again. Nonclassical correlations are shown for a delay of 81ns.[4]

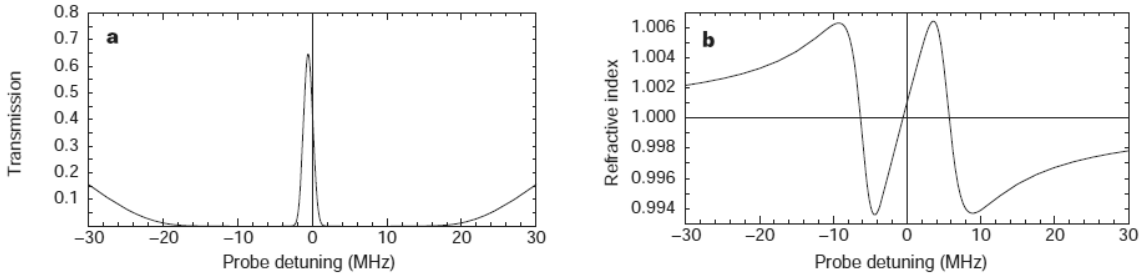

FIG. 6: a. Transmission spectrum of the probe as a function of the probe detuning from resonance in an ultracold sodium gas. b. Refractive index as a function of the probe detuning from resonance in an ultracold sodium gas [6]

to the higher atomic density, and very small Doppler broadening in the condensate, they are able to achieve an extremely steep dispersion curve presented in Fig. 6. This allows for demonstrated groups velocities as low as 17m/s in the BEC at 50nK. Fig. 6a shows the transmission spectrum for the probe field as a function of the probe detuning in the presence of the coupling field. The coupling field allows for a small transparency window by EIT, and creates the steep refractive index curve. The steepness of this curve is inversely proportional

to the group velocity of the probe pulses. The curves in the figures are shifted slightly off resonance. This is due to the AC Stark effect causing a shift in the $|2\rangle \rightarrow |3\rangle$ transition. This shift is proportional to the applied coupling field intensity. By varying the coupling field intensity, the index of refraction refraction changes, yielding a nonlinear index of refraction term which can be useful for quantum optics experiments. By further improving this experiment, the group velocity might even be reduced further, approaching the speed of sound in the BEC. If the group velocity were to reach this level, light propagation could cause phonon excitation in the condenstate[6].

B. Slow Light in a Solid

Slow light propagation has also been demonstrated in a room temperature solid[10]. Bigelow et al., used coherent population oscillations in an alexandrite crystal lattice to reduce the group velocity of light. They modulate a pump beam to generate the probe beam in the side bands. By exciting the coherent population oscillations, a quantum interference effect similar to EIT allows transmission of the probe beam through a narrow spectral hole in the alexandrite transmission spectrum. By using this technique, they were able to observe group velocities as low as 91m/s in a room temperature solid, showing promise for a new technique for the delay of photonic signals.

IV. CONCLUSIONS

Current experiments and theory show promise in the development of quantum storage devices through the use of electromagnetically induced transparency in atomic gases. Storage without distortion of the shape of the probe pulse has been demonstrated in excess of $800\mu s$[3] for weak classical probe pulses, and nonclassical correlations have been observed for up to $3\mu s$[4]. This shows tremendous promise for the development of photonic quantum information storage devices. However, the storage time scales and retrieval efficiencies are still low for these signals. For these devices to become pratical for everyday use, storage times and retrieval efficiencies need to be increased. Theoretical calculations also show promise for manipulating the information during storage in these devices. This shows promise for the field of quantum computation. Further development of these slow light techniques with atomic gases will likely result in pratical quantum memory storage devices in the future.

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