Electromagnetically Induced Transparency:

Toward Quantum Control of Single Photons

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Electromagnetically induced transparency (EIT) is widely used to control the interaction of laser pulses with matter. It results in fascinating effects such as "slow light" and "stopped light." Researchers are exploring ways to use EIT on individual light quanta, laying the groundwork for intriguing applications in quantum information science that use photons as information carriers, and atomic ensembles as memory and processing nodes.

OVER THE PAST DECADE, one of the most exciting challenges for researchers in quantum optics has been to create techniques to facilitate controlled, coherent interactions between single photons and matter. Beyond their fundamental importance in optical science, these interactions could lead to the practical realization of photonic quantum networks, in which single-photon transmission through optical fibers connects a number of memory nodes that use atoms for the generation, storage and processing of quantum states.

Such networks are expected to play a major role in extending the range of quantum communication and quantum cryptography to long distances, and possibly for implementing scalable quantum-information processors. At the same time, techniques for manipulating light propagation may eventually enable researchers to achieve controlled nonlinear interactions between individual photons—which has been a "holy grail" of nonlinear optics for several decades.

Investigators are exploring several promising avenues for achieving such interactions, and remarkable progress has been made in just the past few years. In particular, the cavity QED experiments by Jeff Kimble's group at Caltech and Gerhard Rempe's group at the Max-Planck-Institut für Quantenoptik in Germany have realized strong coupling between single optical photons and single atoms using high-finesse micro-cavities. This approach involves controlled, coherent absorption and emission of photons by single atoms, allowing for the generation and storage of single photons, as well as the creation of nonlinear interactions between them.

Another area that holds great potential involves the manipulation of quantum pulses of light in optically dense atomic ensembles. Here the primary challenge is to control the light-matter interaction and to eliminate the dissipative processes that normally accompany such interactions. For example, last year Eugene Polzik and his colleagues from the Niels Bohr Institute in Copenhagen used a novel approach that combines off-resonant, dispersive interaction with quantum measurements to map quantum states of weak laser pulses onto atoms.

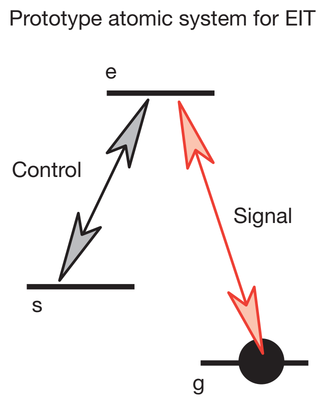
In this article, we describe a technique called electromagnetically induced transparency (EIT), which can be used to achieve the desired control, and review recent advances that have allowed researchers to use EIT for the quantum control of single photons, and their interaction with atomic ensembles.

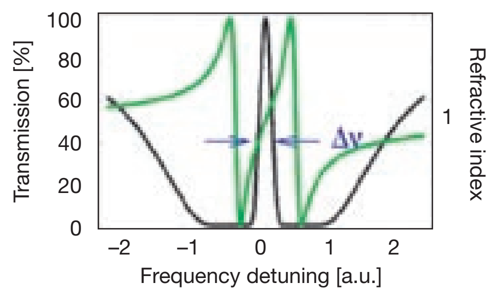
Electromagnetically induced transparency

When the frequency of a laser pulse approaches that of a particular atomic transition, the optical response of the medium is greatly enhanced. Under such conditions, light propagation is typically accompanied by strong absorption and dispersion, as the atoms are driven into fluorescing excited states.

EIT coherently controls light propagation in such a resonant medium. Consider the situation in which the atoms have a pair of long-lived lower energy states $|g\rangle$ and $|s\rangle$ (see figure below). This is the case,

[Electromagnetically Induced Transparency (EIT)]





Spectrum of transmission (black curve) and refractive index (green curve) corresponding to EIT for the signal field. Rapid variation of the refractive index with changing signal frequency causes a reduction of the signal-field group velocity.

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for example, for sublevels of different angular momentum (spin) within the electronic ground state of alkali atoms. In order to modify the propagation of light that couples the ground state |g⟩ to an electronically excited state |e⟩ in such a medium (signal field, red arrow), one can apply a second optical field that is near resonance with the transition |s⟩-|e⟩ (control field, black arrow).

The combined effect of these two fields is to place the atoms into a coherent superposition of the states |g⟩ and |s⟩. In other words, the atoms can simultaneously occupy both states (|g⟩ and |s⟩) with a definite phase relationship, such that the two possible absorption pathways (|g⟩ ⟶ |e⟩ and |s⟩ ⟶ |e⟩) interfere destructively. Under such conditions, none of the atoms are promoted to the excited state, leading to vanishing light absorption. In this way, the EIT control field is used to modify the propagation of the signal field.

The frequency range of induced transparency for the signal field is typically narrow, since the atomic interference effect is very fragile. The tolerance to frequency mismatch can be increased, however, by using a stronger control field, thereby making the interference more robust. This is the essence of EIT, pioneered by Steve Harris and co-workers at Stanford.

From slow light to stationary pulses

Because atoms are decoupled from the light fields under ideal EIT conditions, the refractive index on resonance is nearly equal to unity. However, the narrow transparency window is accompanied by a very steep, nearly linear variation of the refractive index. Different frequency components of a light pulse propagating in the medium thus experience different refractive indices, resulting in a group velocity v_g for the entire pulse that can be much smaller than the speed of light in vacuum c.

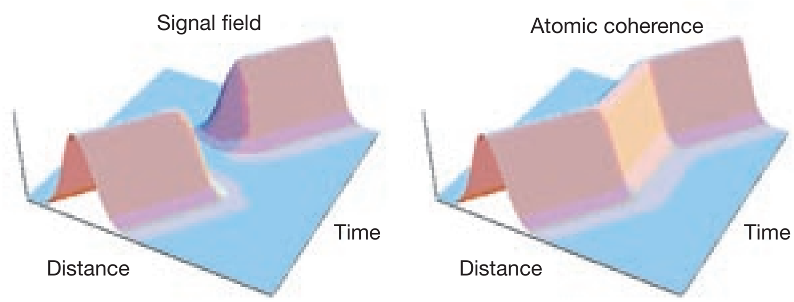
The group velocity v_g depends on the control field intensity and the atomic density. Decreasing the control field power and/or increasing the atom density can lead to extremely slow group velocities for the signal field, allowing the compression of kilometer-long pulses into millimeter-long atom clouds.

The slow propagation of light pulses in the medium is accompanied by a wave of atomic excitations (a so-called spin wave) associated with the coherent superposition of atomic spin states (|g⟩ and |s⟩). The light pulse and spin wave form a combined excitation of photons and spins called a dark-state polariton. The group velocity of this polariton is proportional to the magnitude of its photonic component. As the control intensity is decreased, the group velocity is slowed, implying that the contribution of photons to the polariton state is reduced. In particular, if the control field intensity is reduced to zero, the polariton becomes purely atomic and its group velocity is reduced to zero.

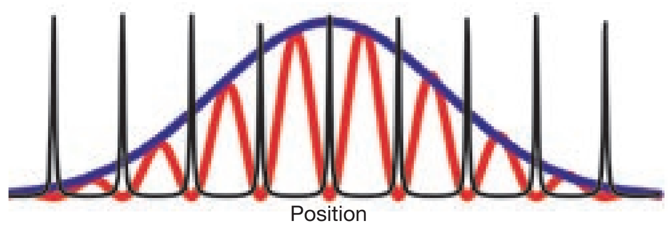
This is the idea behind a number of "light storage" experiments in which weak laser pulses were stopped and stored in spin excitations of atomic vapor. Most important, the stored excitation can then be converted back into a light pulse, propagating in the same or different directions, by reapplication of the corresponding control field.

In more recent work, these ideas have been extended to create an excitation with localized, stationary electromagnetic energy bound to an atomic spin coher-

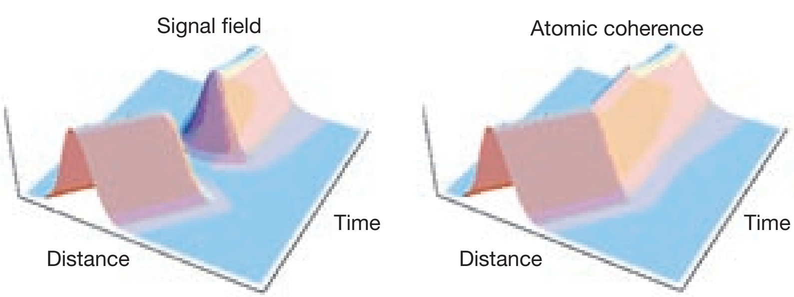
[Stationary Light Pulses]



Storage and retrieval of weak signal pulse in the |g⟩ ⟨s| atomic coherence. Retrieval is performed using a forward-propagating EIT control field.



Spatial variation of signal field absorption (black line), stationary pulse signal field (red line), and atomic spin coherence (blue line), as seen during retrieval, when retrieval is performed with forward- and backward-propagating EIT control fields with equal Rabi frequencies.



Evolution of forward signal component and atomic coherence when retrieval is performed using both forward- and backward-propagating EIT control fields with equal Rabi frequencies.

ence, which can be released after an adjustable time interval. This is of particular interest for nonlinear-optical interactions over long times. In the experiments of Bajcsy et al., an atomic spin wave is created via "light storage" techniques, and then converted into a stationary photonic excitation by simultaneously illuminating the atomic medium with forward- and backward-propagating EIT control fields.

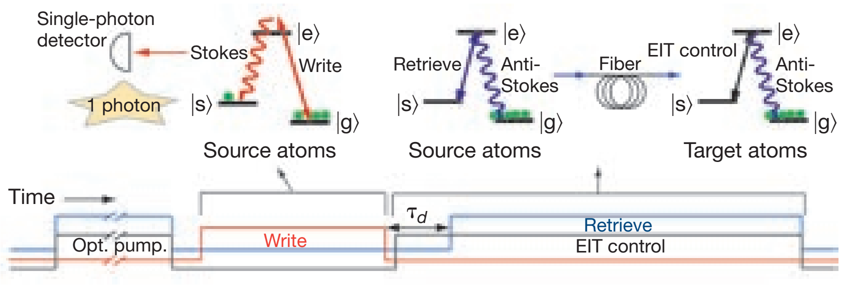
Specifically, if the two fields create a standing wave pattern, EIT suppresses the signal absorption everywhere except in the nodes of the standing wave, resulting in a sharply peaked, periodic modulation of the atomic absorption for the signal light (see figure on previous page). The presence of the control fields also results in a partial conversion of the stored spin excitation into a sinusoidally modulated signal field. The signal field cannot propagate freely in the medium, however, due to Bragg reflections off the sharp absorption peaks, resulting in vanishing group velocity. Only after one of the control beams is turned off does the pulse acquire a finite velocity, leaving the medium in the direction of the remaining control field.

Correlated photon pairs, single photons and light-atom entanglement

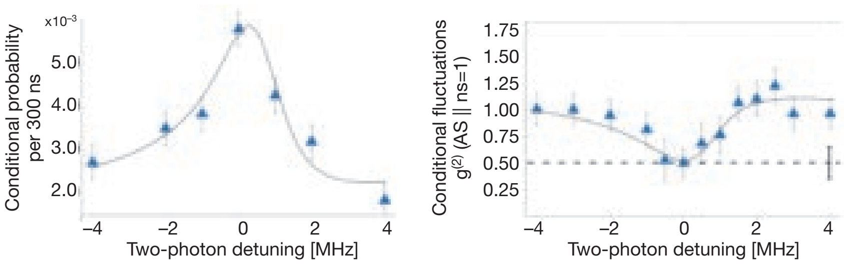
Recently, EIT-based coherent control techniques have been successfully extended to the quantum domain, enabling the generation of correlated photon pairs and frequency-tunable single photons with narrow (MHz) bandwidths, as well as the creation of atom-photon entanglement. [See figure on the right.]

To understand the idea behind these developments, consider an atomic ensemble that is initially prepared in the ground state |g⟩. Atomic spin excitations to the state |s⟩ are produced via spontaneous Raman scattering, induced by a laser beam referred to as the write laser. In this process, pairs of frequency-shifted photons (so-called Stokes photons) and correlated atomic spin excitations are created (corresponding to atomic Raman transitions into the state |s⟩). Energy and momentum conservation ensure that, by detecting a Stokes photon emitted in a

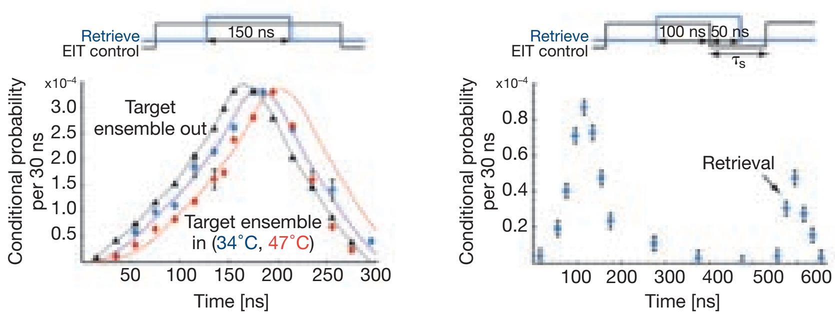
[EIT, slowing and storage of single-photon pulses]



"Source" and "target" ensembles of ^{87}Rb atoms are used. Researchers conditionally generate and transmit single photons to the "target" atomic ensemble, via a polarization-maintaining single-mode fiber. They then illuminate the target ensemble by an EIT control laser resonant with the |s⟩ - |e⟩ transition, creating EIT conditions for the single-photon anti-Stokes pulse. Timing diagram shows the relative turn-on and turn-off times of the various lasers.

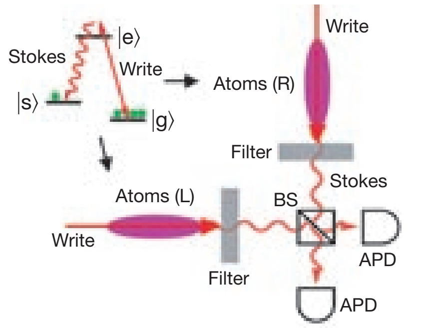


(*Left*) Conditional probability (per 300 ns) of detecting an anti-Stokes photon transmitted through the target ensemble, versus the two-photon detuning (difference between the EIT control / anti-Stokes frequency difference and the |g⟩ - |s⟩ frequency difference). (*Right*) Photon-number fluctuations of the anti-Stokes field, conditioned on detecting one Stokes photon. Dotted line and error bar represent measured value with no target ensemble present. The solid line is the result of a theoretical model.



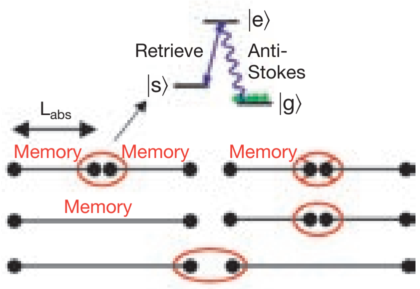
(*Left*) EIT-based single-photon pulse delay. Conditional probability (per 30 ns) of detecting an anti-Stokes photon transmitted through the target ensemble. Target ensemble absent (black triangles); target ensemble present at 34.6° C (blue diamonds) and 47° C (red diamonds). Delayed pulse at (34.6° C, 47° C) is scaled by (1.34, 2.14). Solid lines represent theoretical calculations for EIT propagation in a Doppler-broadened medium. (*Right*) Storage and retrieval of a single-photon anti-Stokes pulse. EIT control is turned off 100 ns after the retrieval from the source ensemble begins; after waiting for a storage time of τ_s = 480 ns, the EIT control is turned back on, resulting in the retrieved pulse centered at 600 ns.

[Atomic-Ensemble-Based Quantum Repeater]



FIRST STEP: Entanglement generation. Interference of spontaneous Stokes photons from two ensembles (R and L) on a beam-splitter (BS) leads to generation of entanglement between the corresponding spin modes in the ensembles, provided a single Stokes photon was detected in one of the avalanche photo detectors (APD). If zero or two photons are detected, the process must be repeated.

SECOND STEP: Entanglement swapping. The entanglement between atomic ensembles created over a characteristic absorption length L_{abs} in the first step, indicated here by filled circles connected by a line, is extended to two absorption lengths via entanglement swapping. By repeating this process, long-distance entanglement is created. Entanglement swapping is accomplished by interference of anti-Stokes photons on a beam splitter and detection (as in step one), provided a single anti-Stokes photon has been measured. In such a probabilistic scheme, the "memory" (i.e., the nonzero decay time of the |g⟩ - |s⟩ coherence) is essential for polynomial scaling of the required time with distance (compared to exponential scaling for the case of direct entanglement generation).



particular direction, the atomic ensemble is prepared in state with exactly one flipped spin quantum in a well-defined spin-wave mode.

Thus, conditioned upon detecting a single Stokes photon, a single stored spin-wave quantum is created. It can be coherently converted into a single anti-Stokes photon by applying a second near-resonant laser beam (retrieve laser) after a controllable delay time. The physics of this retrieval process is similar to that of early "light storage" experiments, with the anti-Stokes field propagating through the source ensemble under EIT conditions; the retrieve laser acts as the EIT control field and prevents the absorption of the anti-Stokes field by the atomic population in state |g⟩.

The direction, bandwidth and central frequency of the single-photon anti-Stokes pulse is determined by the direction, intensity and frequency of the retrieve laser; specifically, the central frequency of the single-photon pulse differs from the frequency of the retrieve laser by a fixed amount given by the |g⟩ - |s⟩ atomic transition frequency.

Two years ago, our research team and Jeff Kimble's group at Caltech used this method to generate nonclassically correlated photon fields from atomic ensembles. Recently, Steve Harris' group at Stanford achieved the generation of correlated photon pairs with controllable pulse envelopes using ^{87}Rb in a magneto-optical trap (MOT); the photon pairs in these experiments exhibited an exceptionally high degree of correlation. In addition, these experiments were able to reach a new regime where Rabi oscillations of the atomic populations resulted in the oscillation of the photon correlations in time.

To demonstrate the generation of single anti-Stokes photons conditioned on detecting a single Stokes photon, researchers can measure the photon-number fluctuations in the anti-Stokes channel by means of a Hanbury-Brown-Twiss type setup. In our recent experiments, we generated single-photon pulses with photon-number fluctuations suppressed by a factor of four relative to the classical limit of an ideal laser, using a room-temperature ^{87}Rb cell. Similar results were first obtained last year by Jeff Kimble's group at Caltech using a MOT of Cs atoms.

When Raman scattering occurs in multiple channels, quantum correlations are generated between specific atomic spin modes and corresponding spatial modes of the Stokes field. This can be used to create entanglement between a photon and an atomic excitation. Alex Kuzmich and his colleagues at Georgia Tech demonstrated such entanglement by using a pair of atomic Zeeman states. Finally, very recently, Vladan Vuletic's team at MIT used a Cs MOT inside a high-finesse optical resonator to convert atomic-ensemble excitations into photons with very high efficiency.

Using EIT to slow and store single photons

Before quantum networks can become a reality, researchers must learn how to control the interaction between single photons and atomic memory nodes. In particular, they must be able to reversibly exchange quantum states between photons and atoms. We recently took a step toward these goals by demonstrating single-photon EIT, as well as the EIT-based slowing and storage of narrow-bandwidth, frequency-tunable single photons.

In these experiments, single photons were generated in one atomic ensemble ("source") using the method described above, and then sent to a second ("target") atomic ensemble via an optical fiber. A separate EIT control beam was used to create EIT for single photons in the target ensemble. We observed that the suppressed photon-number fluctuations associated with the single-photon pulses were preserved when the single-photon frequency was tuned within the EIT transparency window.

These EIT-based techniques enabled us to slow the group velocity of the single-photon pulses to about 1/300 of the vacuum speed of light and localize more than 30 percent of incident pulse in a few-centimeter-long ensemble.

Finally, by modulating the intensity of the EIT control beam illuminating the target ensemble, we were able to store the localized fraction of the incident single photons and retrieve the stored pulses after microsecond-long time intervals. Correlation measurements showed that some degree of non-classical correlations was preserved after storage and retrieval. Similar results were recently achieved by Alex Kuzmich's group at Georgia Tech using two separated MOTs. The team used this technique to create entanglement between two remote ensembles.

This method for single-photon generation, storage and retrieval has an important advantage: Because the single photons are generated in the first ensemble under EIT conditions, their central frequency and bandwidth can be easily matched to the EIT transparency resonance of the second ensemble by tuning the retrieve and EIT control lasers.

Quantum repeaters and single-photon nonlinear optics

Clearly these early demonstrations must be improved upon in order to be useful for quantum-information applications. The storage fidelity could be enhanced by increasing the optical depth, for example, or by using an optical cavity with modest finesse—an approach that is currently under investigation by Vladan Vuletic's team at MIT. The storage times could be considerably extended by reducing the effect of atomic diffusion, working with ultra-cold atoms in dipole traps or optical lattices, or, as demonstrated very recently by Neil Manson and colleagues in Canberra, using doped glasses.

Much of the recent work on single-photon generation and storage has been motivated by a proposal by L.M. Duan and colleagues for long-distance quantum communication. Laser-induced Raman scattering can be used to implement the backbone of this protocol—the probabilistic generation of quantum entanglement of two atomic ensembles using an absorbing photonic channel. Synchronized classical pump pulses illuminate the two ensembles. The forward-scattered Stokes photons interfere at a 50 percent-50 percent beam splitter, with the outputs detected, respectively, by two single-photon detectors.

In such a configuration, a single detector click implies that one quantum of spin excitation has been created in one of the two ensembles. However, it is fundamentally impossible to determine from which of the two ensembles the photon arrived. In this case, the measurement projects the state onto an entangled state of the two ensembles.

Alex Kuzmich and co-workers have already observed quantum correlations between two ensembles. In a very recent experiment, Jeff Kimble's group carefully measured the generated entanglement between two ensembles separated by a large distance.

The most remarkable feature of this process is that it can be made robust with respect to imperfections and losses during the optical propagation. In particular, when the losses in left and right optical paths are equal, the total loss will affect the overall probability of success but not the purity of the resulting state conditioned on the detection of a single Stokes photon. These techniques for probabilistic manipulation of atomic ensembles may have interesting applications for long-distance quantum communication over realistic photonic channels, where absorption leads to an exponential decrease of the signal.

The second application of these techniques involves coherent nonlinear-optical interactions at the single-photon level that can be envisioned by combining these techniques with resonantly enhanced atomic nonlinearities or direct interaction between atomic spin states. For example, Axel André and co-workers recently suggested combining the techniques of stationary pulses with resonantly enhanced Kerr nonlinearities to create efficient nonlinear interaction between two single-photon pulses.

This proposal is an extension of earlier theoretical work by Atac Imamoglu and coworkers. How to realize such techniques experimentally remains an outstanding challenge, since there is no collective enhancement of the nonlinear interaction strength. The advantage of using ensembles of atoms is that they enhance the interaction time of the photons.

For very small group velocities, the character of the polaritons is mainly atom-like; thus, several groups suggested making use of the spin component of the polaritons and coherent atom-atom interactions to induce a nonlinear phase shift between two counter-propagating single-photon polaritons. In all these cases, a major practical challenge is attaining the required transverse compression of the pulses to an area comparable to the square of the optical wavelength. Techniques to manipulate stationary light pulses may prove useful for solving this problem.

In the coming years, these advances will lead to exciting experimental developments in the applications of EIT-based techniques to quantum communication and controlled nonlinear interactions of quantum pulses of light.

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