Interaction between Two Stopped Light Pulses

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***Motivation***

- Photons are superior information carriers: ultimate speed, inert to the environment, no collision with each other $\Rightarrow$ Ideal for quantum information.

- One qubit = single photon, so qubit-qubit operation or photon-photon interaction: nonlinear optical process.

- Nonlinear efficiency $= (\text{transition rate}) \times (\text{interaction time})$, but transition rate $\propto$ light intensity and is usually very low at single-photon level.

- Stopping light pulses and making them interact can greatly enhance the interaction time $\Rightarrow$ A sufficient nonlinear efficiency can be achieved even at single-photon level.
Outline

- Electromagnetically induced transparency (EIT), slow light, and storage of light.
- Experimental setup.
- Cross-phase modulation (XPM) and all-optical switching (AOS) based on stored light.
- Stationary light in cold atoms.
- Interaction between two stopped light pulses.
- Conclusion.
The Phenomenon of Electromagnetically Induced Transparency (EIT)

Large Optical Density (OD), defined by $I_{\text{out}} = I_{\text{in}} e^{-\text{OD}}$. 

Diagram:
- Probe laser
- Coupling laser
- Atoms

States:
- $|1\rangle$
- $|2\rangle$
- $|3\rangle$
• Near the resonance, probe transmission \( \sim 0 \), because \( \text{OD} \approx 7 \) \( (I_{\text{out}} = I_{\text{in}} e^{-\text{OD}}) \).
• Narrow-width & high-contrast absorption profile => large dispersion => slow group velocity.
The medium length was 1~2 mm and speed of the light pulse $\leq 600$ m/s.

After the coupling field is quickly turned off, the gap of $\sim 5 \mu$s in the probe signal demonstrates the storage of the probe pulse. $\tau_{coh} \sim 10 \mu$s.
i) The two-photon transition that absorbs probe photons.

ii) All the probe photons are absorbed; the ground-state (Raman) coherence or spin excitation still remains in the atoms.

iii) The retrieval is the reversal process.

The EIT storage is a coherent process and provides a method for exchange of wave functions between photons and atoms.
• We produce $10^9^{87}$Rb atoms with a temperature of 300 µK with a magneto-optical trap (MOT).

• Coherence time ($\tau_{\text{coh}}$) $\sim$ 100 µs & optical density (OD) $\geq$ 190.

• EIT physics can work in any of the 3-level systems of other atomic species, room-temperature atoms, solids, quantum wells/dots, etc.
EIT Experiment

8 diode lasers; MOPA; UHV system; > 300 optical components

simple physics system; complicate experimental setup
Magneto-Optical Trap

Dimension: $9.2 \times 1.8 \times 1.8 \ mm^3$
We report a 78% storage efficiency, which is the best record of the EIT-based memory.

High Fidelity of the EIT Storage


\[ F \text{ (fidelity)} = \frac{|\langle \psi_{\text{in}} | \psi_{\text{out}} \rangle|^2}{\langle \psi_{\text{in}} | \psi_{\text{in}} \rangle \langle \psi_{\text{out}} | \psi_{\text{out}} \rangle} \]
\[ = \frac{\left| \int E_{\text{in}}^*(t - t_d) E_{\text{out}}(t) dt \right|^2}{\left[ \int |E_{\text{in}}(t)|^2 dt \right] \left[ \int |E_{\text{out}}(t)|^2 dt \right]} \]

- The theoretical \( F = 0.97 \) due to the broadening of the output pulse.
- \( F = 0.94 \) @ storage time of 7 \( \mu s \); \( F = 0.90 \) @ 55 \( \mu s \) due to (S/N).
**Cross-Phase Modulation (XPM) based on Stored Light**


- The stored coherence is equivalent to the probe pulse.
- During the storage, a signal pulse induces the AC Stark shift and changes the frequency and, hence, the phase of the ground-state coherence.
- Therefore, the phase of the retrieved probe pulse is also modulated.
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Therefore, the phase of the retrieved probe pulse is also modulated.
A phase shift of $44^\circ$ with a transmission of 65% is obtained at 18 photons per $3\lambda^2/(2\pi)$ (atomic absorption cross section).

Phase shifts of the order of $\pi$ with single photons: quantum phase gates, entangled photon pairs, quantum nondemolition measurements.

How to further improve?
Stationary Light Pulses (SLPs)

A light pulse is actually stopped while maintaining its EM wave.

Simultaneously switching on the forward and backward coupling fields makes the probe stationary.
Formation of SLPs

Coupling \( \rightarrow \Omega_+^e e^{ik_+^cz} + \Omega_-^e e^{-ik_-^cz} \)

Probe \( \rightarrow \Omega_+^p e^{ik_+^pz} + \Omega_-^p e^{-ik_-^pz} \)

Optical Coherence \( \rightarrow \rho_{31}^+ e^{ik_+^pz} + \rho_{31}^- e^{-ik_-^pz} \)

Assume \( k_+^c \approx k_+^p \); \( k_-^c \approx k_-^p \)

Neglect \( e^{inkz} \) terms for \( n \geq 2 \)

\[
\begin{align*}
\frac{\partial \rho_{21}}{\partial t} &= \frac{i}{2} (\Omega_+^c)^* \rho_{31}^+ + \frac{i}{2} (\Omega_-^c)^* \rho_{31}^- - \gamma \rho_{21}, \\
\frac{\partial \rho_{31}^+}{\partial t} &= \frac{i}{2} \Omega_+^p + \frac{i}{2} \Omega_+^c \rho_{21} - \frac{\Gamma}{2} \rho_{31}^+, \\
\frac{\partial \rho_{31}^-}{\partial t} &= \frac{i}{2} \Omega_-^p + \frac{i}{2} \Omega_-^c \rho_{21} - \frac{\Gamma}{2} \rho_{31}^-, \\
\frac{1}{c} \frac{\partial \Omega_+^p}{\partial t} + \frac{\partial \Omega_+^p}{\partial z} &= \frac{i}{2L} \rho_{31}^+, \\
\frac{1}{c} \frac{\partial \Omega_-^p}{\partial t} - \frac{\partial \Omega_-^p}{\partial z} &= \frac{i}{2L} \rho_{31}^-.
\end{align*}
\]

Timing Sequence of Coupling Fields
Forward and Backward Probe Pulses as Functions of \( z \) and \( t \)

With (c) & (d) Destroy (c) & (d)

SLPs in Cold Atoms


Without detuning

With detuning

With (c) & (d) Destroy (c) & (d)

EIT-based XPM and AOS

Cross-Phase Modulation (XPM): phase shift ($\phi$) = $\frac{\psi (N/A) \sigma}{4}$ at $|\Delta_s| = \Gamma/2$

All-Optical Switching (AOS): attenuation ($R$) = $\exp[-\psi (N/A) \sigma]$ at $\Delta_s = 0$

where $\psi$ is nonlinear efficiency depending on the operation scheme and $(N/A)\sigma$ is number of photons per absorption cross section.

S. E. Harris & Y. Yamamoto, PRL 81, 3611 (1998)
AOS with Moving Pulses

\[ \text{AOS attenuation} = \exp\left[-\psi \left(\frac{N}{A}\right)\sigma_a \right] \]

Experimentally, with moving light pulses, we showed \( \psi \approx 0.45 \) is the limit.

S. E. Harris & L. V. Hau, “Nonlinear Optics at Low Light Levels,” PRL 82, 4611 (1999): Theoretically, at a very large OD, \( \psi \to 0.5 \).
Two Stopped Light Pulses

Two EIT Systems

- Store probe pulse in the atoms and make signal pulse stationary in the same medium.
- Use stationary signal to switch stored probe.
- Ideally, the interaction time can be as long as possible.

780nm $|F' = 2\rangle$

795nm $|F' = 1\rangle$

Stationary Signal

Probe Coherence

Probe
AOS with Stopped Light Pulses


$$AOS \text{ attenuation} = \exp[-\psi \,(N/A)\sigma_a]$$

- With stopped light pulses, $\psi \approx 1.8$ or the switch was achieved at 0.56 photons per atomic absorption cross section $\Rightarrow$ 4-fold improvement.
- Most importantly, $\psi$ has no upper limit and can be further improved by increasing OD.
Frozen “light switch”

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