Quantum Memory with Atomic Ensembles

Yong-Fan Chen 陳泳帆
Physics Department, Cheng Kung University
Outline

- Laser cooling & trapping
- Electromagnetically Induced Transparency (EIT)
- Slow light & Stopped light
- Manipulating light with light-storage techniques
- Quantum applications with atomic ensemble (DLCZ scheme)
Manipulating atoms with photons*

Claude N. Cohen-Tannoudji
Collège de France et Laboratoire Kastler Brossel\textsuperscript{1} de l'Ecole Normale Supérieure, 75231 Paris Cedex 05, France.


The Nobel Prize in Physics 1997

"for development of methods to cool and trap atoms with laser light"

Steven Chu
1/3 of the prize
USA
Stanford University
Stanford, CA, USA
b. 1948

Claude Cohen-Tannoudji
1/3 of the prize
France
Collège de France; École Normale Supérieure
Paris, France
b. 1933
(in Constantine, Algeria)

William D. Phillips
1/3 of the prize
USA
National Institute of Standards and Technology
Gaithersburg, MD, USA
b. 1948
Magneto-optical trap (MOT)

Ultracold atoms produced by laser cooling and trapping

From ultracold atom Lab @ NTHU
10 K ultracold atoms

\[ T = 0.00001 \text{ K} \]
\[ t_1 = 10 \text{ ms} \]
\[ t_2 = 30 \text{ ms} \]
\[ \Delta x = 4 \text{ mm} \]
Image of ultracold atoms

From ultracold atom Lab @ NTHU
Resonant interaction of an atom with light allows coherent manipulation of light and atomic states.

- However, single atom absorption cross-section $\sim \lambda^2$
- Cavity QED: fascinating but not easy experiment!!

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K. Vahala (Caltech)
J. Kimble (Caltech)
G. Rempe (MPQ)
H. Walter (MPQ)
Y. Yamamoto (Stanford)

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**Atomic Ensembles-Light Interaction**

Interaction of light field and many atoms is strong (collective enhancement), but incoherent (spontaneous emission)

- Need: techniques for coherent control of resonant optical properties
- Idea: suppress the resonant absorption & coherent control light propagating in many atom system (atomic ensembles)

- Electromagnetically Induced Transparency (EIT)

Coupled propagation of photonic and spin wave: dark-state polaritons

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Nonlinear Optical Processes Using Electromagnetically Induced Transparency

S. E. Harris, J. E. Field, and A. Imamoğlu

*Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305*

(Received 27 December 1989)

We show that by applying a strong-coupling field between a metastable state and the upper state of an allowed transition to ground one may obtain a resonantly enhanced third-order susceptibility while at the same time inducing transparency of the media. An improvement in conversion efficiency and parametric gain, as compared to weak-coupling field behavior, of many orders of magnitude is predicted.

PACS numbers: 42.65.Ky, 42.50.Hz, 42.50.Qg
Electromagnetically Induced Transparency (EIT)

\[ \chi_{\text{EIT}}(\omega_p) = N \frac{3\lambda^3}{4\pi^2} \left( \frac{\Gamma}{4} \right) \frac{\Delta_p - i\Gamma - \frac{\Omega_c^2}{4(\Delta_p - i\gamma)}}{\Delta_p - i\Gamma - \frac{\Omega_c^2}{4(\Delta_p - i\gamma)}} \]

(a) Diagram showing the coupling process
(b) Normalized real part of \(\chi(\omega_p)\) without and with coupling
(c) Normalized imaginary part of \(\chi(\omega_p)\) without and with coupling

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**EIT : Quantum Interference**

\[ |g_1\rangle \rightarrow |e\rangle = |A_i + A_{ii} + A_{iii} + \cdots|^2 \]

\[ \Rightarrow \text{The probe absorption is suppressed.} \]
EIT : dark-state picture

Coherent Population Trapping (CPT)

\[
\langle 3 \mid H_{\text{probe}} + H_{\text{coupling}} \mid D \rangle = 0
\]

\[
|D\rangle = \frac{\Omega_c}{\sqrt{\Omega_c^2 + \Omega_p^2}}|1\rangle - \frac{\Omega_p}{\sqrt{\Omega_c^2 + \Omega_p^2}}|2\rangle
\]

\[
|B\rangle = \frac{\Omega_p}{\sqrt{\Omega_c^2 + \Omega_p^2}}|1\rangle + \frac{\Omega_c}{\sqrt{\Omega_c^2 + \Omega_p^2}}|2\rangle
\]

EIT Condition : \( \Omega_p << \Omega_c \)
Observation of Electromagnetically Induced Transparency

K.-J. Boller, A. Imamoglu, and S. E. Harris

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305
(Received 12 December 1990)

We report the first demonstration of a technique by which an optically thick medium may be rendered transparent. The transparency results from a destructive interference of two dressed states which are created by applying a temporally smooth coupling laser between a bound state of an atom and the upper state of the transition which is to be made transparent. The transmittance of an autoionizing (ultraviolet) transition in Sr is changed from $\exp(-20)$ without a coupling laser present to $\exp(-1)$ in the presence of a coupling laser.
EIT experiment in cold $^{87}$Rb atoms

$|F'=3\rangle$, $|F'=2\rangle$, $|F'=1\rangle$

$5P_{3/2}$

$|F=2\rangle$, $|F=1\rangle$

$5S_{1/2}$

$m = -2 \quad -1 \quad 0 \quad 1 \quad 2$

Probe

Coupling

Repumping

Trapping

BS

M

Aperture

Block

OSC

PD

ECDL

DL

AOM

EOM

Master
EIT Spectrum

\[ \text{Sweep rate} = 2.5 \, \text{Γ}/\text{ms} \]
\[ \Omega_c = 0.4 \, \text{Γ}, \quad \text{Δ} = 0.002 \, \text{Γ} \]
\[ \Omega = 2 \, \text{Γ} \, 5.9 \, \text{MHz} \]

\[ V_g \equiv \frac{d\omega}{dk} = \frac{c}{n + \left(\frac{dn}{d\omega}\right)\omega} \]

“Slow Light” in cold Na atoms

“Slow Light” in cold $^{87}$Rb atoms

$\text{Delay time} \sim 2 \mu s$

$V_g \sim 500 \text{ m/s}$

$T_D = (\Gamma/\Omega_c^2)n\sigma L$

Can we stop or trap light?
Dark-State Polaritons in Electromagnetically Induced Transparency

M. Fleischhauer\(^1\) and M. D. Lukin\(^2\)

\(^1\)Sektion Physik, Ludwig-Maximilians-Universität München, Theresienstrasse 37, D-80333 München, Germany
\(^2\)ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
(Received 26 January 2000)

\[ \hat{E}(z,t) \]

\[ \Omega(t) \]

\[ \Psi(z,t) = \cos\theta(t)\hat{E}(z,t) - \sin\theta(t)\sqrt{N}\sigma_{bc}(z,t) \]

\[ \cos\theta(t) = \frac{\Omega(t)}{\sqrt{\Omega^2(t) + g^2N}} \]

\[ \sin\theta(t) = \frac{g\sqrt{N}}{\sqrt{\Omega^2(t) + g^2N}} \]

Strong coupling field (\( \theta \to 0 \)): Polaritons: purely photonic wave

Weak coupling field (\( \theta \to \pi/2 \)): Polaritons: larger parts in spin wave

Dark-State Polaritons: Coupled propagation of photonic and spin wave

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Cold atoms


Hot atoms

D. Phillips et al. PRL 86, 783 (2001)
Experiment: Atomic ensembles

Cold atoms

Hot atoms

Yu’s group
U. Tsing Hua

Kimble’s group
Caltech

Walsworth’s group
U. Harvard
Light Storage and Retrieval in cold $^{87}\text{Rb}$ atoms

Storage time $\sim 15 \ \mu s$
Recent Development: Extending storage time

Solid material: Pr$^{3+}$ doped Y$_2$SiO$_5$
Pr: Praseodymium (锺)

Storage time $\sim$ 1 s

Phase ? & How to measure ?
Reference Beat Note: $E_z^2 + E_f(t)^2 + 2E_z E_f(t) \cos(\omega_a t + \phi_r)$

Probe Beat Note: $E_z^2 + E_f(t)^2 + 2E_z E_f(t) \cos(\omega_a t + \phi_p + \Delta\phi)$

- $\phi_r$ and $\phi_p$ are the phases that result from the optical paths, the AOM switching, or other factors.
- $\Delta\phi$ is the phase shift induced by the atoms.
- Although $\phi_r$ and $\phi_p$ vary from one pulse to another, their difference is always fixed.

Phase Coherence of Storage and Retrieval

Quantum Storage
Low-Light-Level Phase Measurement

Phase measurement of weak probe pulses with peak power ~ 400 pW

Manipulating light via light-storage techniques
“Width” manipulation of stored light pulse

Diagram showing the process of storing and manipulating light pulses with spin coherence and probe coupling.

Graphs illustrate the probe transmission over time for different scenarios, labeled (a), (b), (c), and (d), with time in microseconds on the x-axis and probe transmission on the y-axis.

Key values associated with the graphs include:
- (a): 0.30
- (c): 0.45
- (b): 0.30
- (d): 0.28
“Width” manipulation of stored light pulse

\[ \tau' (\mu s) \propto \left( \frac{1}{\Omega_c^R} \right)^2 (\Gamma^{-2}) \]

\[ \Delta \phi \text{ (radians)} \]

“Polarization” manipulation of stored light pulse

\[ m = -2 \quad -1 \quad 0 \quad 1 \quad 2 \]

\[ m = -2 \quad -1 \quad 0 \quad 1 \quad 2 \]

87Rb

5P_{3/2} \quad |F'=2\rangle

5S_{1/2} \quad |F=2\rangle \quad |F=1\rangle

Input Probe

Retrieved Probe

Probes

AOM

Coupling 1

s-polarization

Coupling 2

p-polarization

\[ \lambda/4 \]

Atoms

PD1

PD3

PD4

\[ \Omega_c (\Gamma) \]

Probe Transmission

Time (µs)

(d)

(e)

(f)

Idea!
“Wavelength” manipulation of stored light pulse

Idea!

$^{87}\text{Rb}$

$5P_{3/2}$

$|F'=2\rangle$

Input Probe

Coupling

$\Delta$

$5S_{1/2}$

$|F=2\rangle$

$|F=I\rangle$

Probe Transmittance

Beat Note

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Can we manipulate the “phase” of stored light pulse?
Cross-Phase-Modulation (XPM) based on EIT Theory

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**Fig. 1.** Conventional XPM scheme: $\omega_a$, $\omega_b$ are the frequencies of the incident light fields. $\Delta \omega_a$, $\Delta \omega_b$ are the frequency detunings from level $|i\rangle$ and $|u\rangle$, and $\Gamma_i$, $\Gamma_u$ are the decay rates of states $|i\rangle$ and $|u\rangle$.

**Fig. 2.** Four-level scheme for highly efficient XPM. $\omega_1$, $\omega_2$ are the frequencies involved in the nonlinear process. $\Delta \omega_k$ is the frequency detuning from level $|4\rangle$ ($\Delta \omega_k = \omega_{31} - \omega_k = 0$). $\Gamma_3$, $\Gamma_4$ are the decay rates. Levels $|2\rangle$ and $|3\rangle$ are coherently coupled with Rabi frequency $\Omega_1$. The $|1\rangle-|3\rangle$ transition exhibits EIT. Inset, EIT scheme in the dressed-state basis.

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**Table 1.** Values for Dissipative Susceptibility (Third Order for EIT Scheme and Linear for Three-Level Scheme), XPM Susceptibility, and the Ratio of XPM Phase Shift and Total Absorption for the Proposed EIT Scheme and the Three-Level System of Fig. 1

<table>
<thead>
<tr>
<th></th>
<th>EIT Scheme</th>
<th>Three-Level Scheme</th>
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<tbody>
<tr>
<td><strong>Loss</strong></td>
<td>$N</td>
<td>\mu_{12}</td>
</tr>
<tr>
<td><strong>Re[$\chi^{(3)}$]</strong></td>
<td>$N</td>
<td>\mu_{12}</td>
</tr>
<tr>
<td>$\Phi_{XPM}/(\alpha L)$</td>
<td>$\frac{-\Delta \omega_k}{\Gamma_4}$</td>
<td>$\frac{</td>
</tr>
</tbody>
</table>

Cross-Phase-Modulation (XPM) based on EIT Experiment

FIG. 3. Measured quadrature signals [(a1)–(a3)] and in-phase signals [(b1)–(b3)] versus the signal detuning $\Delta$ while $\Delta_e = \Delta_p = 0$. The solid (dotted) lines are the experimental (theoretical) results. The fitting parameters are $\gamma = 0.01$ MHz, $\Omega_e = 2$ MHz, $\Omega_p = 0.1$ MHz, and $\Omega = 1, 1.7, \text{ and } 3$ MHz, respectively (from the top to the bottom).

FIG. 4. Measured probe absorption [(a) and (c)] and probe dispersion [(b) and (d)] versus the probe detuning $\Delta_p$ while $\Delta_e = \Delta = 0$. The solid (dotted) lines represent the experimental data (the theoretical calculations). (a) and (b) show the EIT spectra of the absorption and dispersion (the signal laser is turned off). (c) and (d) show the probe spectra with the signal laser present. The fitting parameters are $\gamma = 0.01$ MHz, $\Omega_e = 3$ MHz, $\Omega_p = 0.1$ MHz, and $\Omega = 3$ MHz.

Phase shift $\sim 7.5^\circ$

“Phase” manipulation of stored light pulse

**Idea!**

87Rb

\[ \begin{align*}
|F' = 3\rangle & \quad |F' = 2\rangle & \quad |F' = 1\rangle & \quad |F' = 0\rangle \\
5P_{3/2} & \quad F' = 2 & \quad |F = 2\rangle & \quad |F' = 1\rangle & \quad |F' = 0\rangle \\
5S_{1/2} & \quad |F = 1\rangle & \quad |F = 2\rangle & \quad |F' = 1\rangle & \quad |F' = 0\rangle \\
\end{align*} \]

**Interaction of photonic field and atomic spin state!**

\[ \begin{align*}
\phi &= -\frac{\Omega^2 \Delta}{\Gamma^2 + 4\Delta^2} \tau \\
\alpha &= \frac{\Omega^2 \Gamma}{\Gamma^2 + 4\Delta^2} \tau \\
\phi / \alpha &= \frac{\Delta}{\Gamma}
\end{align*} \]
Low-light-level cross-phase modulation based on stored light pulses
Low-light-level cross-phase modulation based on stored light pulses

6 photons per $\frac{\Delta}{2}/2\pi$

$\phi \sim \frac{\Delta}{4}$

$\Delta \sim 0.43$

$\phi / \alpha = \frac{\Delta}{\Omega} \sim 1.79$

Cavity QED: Single-photon $\pi$-phase gate?

Idea!

$T_s$: Spin coherence lifetime

Signal photon  Probe photon

Cavity

Atoms

$|e\rangle$  $|g_1\rangle$  $|g_2\rangle$

Coupling

Retrieved photon

$\phi/\alpha \sim 3.14/0.46 \sim 6.8$

$\phi/\alpha = \frac{\Delta}{\Gamma}$  $\Delta \sim 6.8\Gamma$

$\phi = -\frac{\Omega^2\Delta}{\Gamma^2 + 4\Delta^2} \tau \sim 0.11$

$\alpha = \frac{\Omega^2\Gamma}{\Gamma^2 + 4\Delta^2} \tau \sim 0.016$

Single-photon $\pi$-phase gate is possible!

But still need more efforts!!!
Quantum applications with atomic ensemble
(DLCZ scheme)
DLCZ Scheme

Long-distance quantum communication with atomic ensembles and linear optics

L.-M. Duan\textsuperscript{*}, M. D. Lukin\textsuperscript{†}, J. I. Cirac\textsuperscript{*} & P. Zoller\textsuperscript{*}

\textsuperscript{*} Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria
\textsuperscript{†} Laboratory of Quantum Communication and Computation, USTC, Hefei 230026, China
\textsuperscript{‡} Physics Department and ITAMP, Harvard University, Cambridge, Massachusetts 02138, USA

Recent Development: Single-photon storage

**Summery and Outlook**

- **Storage and Retrieval of Photonic Information**
  - Phase coherent of light storage and retrieval
- **Manipulating the Optical Properties of Stored Light Pulses**
  - Manipulating the retrieved width of stored light pulses
  - Wavelength and Polarization manipulation of retrieved light pulses
- **Light-Storage Cross-Phase Modulation (XPM)**
  - Demonstration of light-storage XPM scheme
- **Outlook**
  - Storage & Manipulation of nonclassical photon pulse (Quantum Memory)
  - Single-photon switching & Single-photon $\pi$-phase gate (Cavity QED + Atomic Ensemble)
  - Quantum networks and communications with atomic ensembles (DLCZ Scheme)
  - Quantum memory and manipulation in a solid
Thanks to

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陳岳男 (NCKU)
Thank you for your attention

- 研究室：49301室；分機：65221
  量子光學實驗室：物二館一樓49117

- Group member
  碩士生 2 名；大學生 2名

- Group meeting
  每個星期二下午4點在物二館1樓49101室

- 實驗室目前的研究方向
  1) 雷射冷卻及捕捉低溫原子
  2) 光子與原子群的量子干涉效應
  3) 光子與原子群的量子態轉換機制