# Slow, Storing, and Stationary Light Pulses for Quantum Information Manipulation

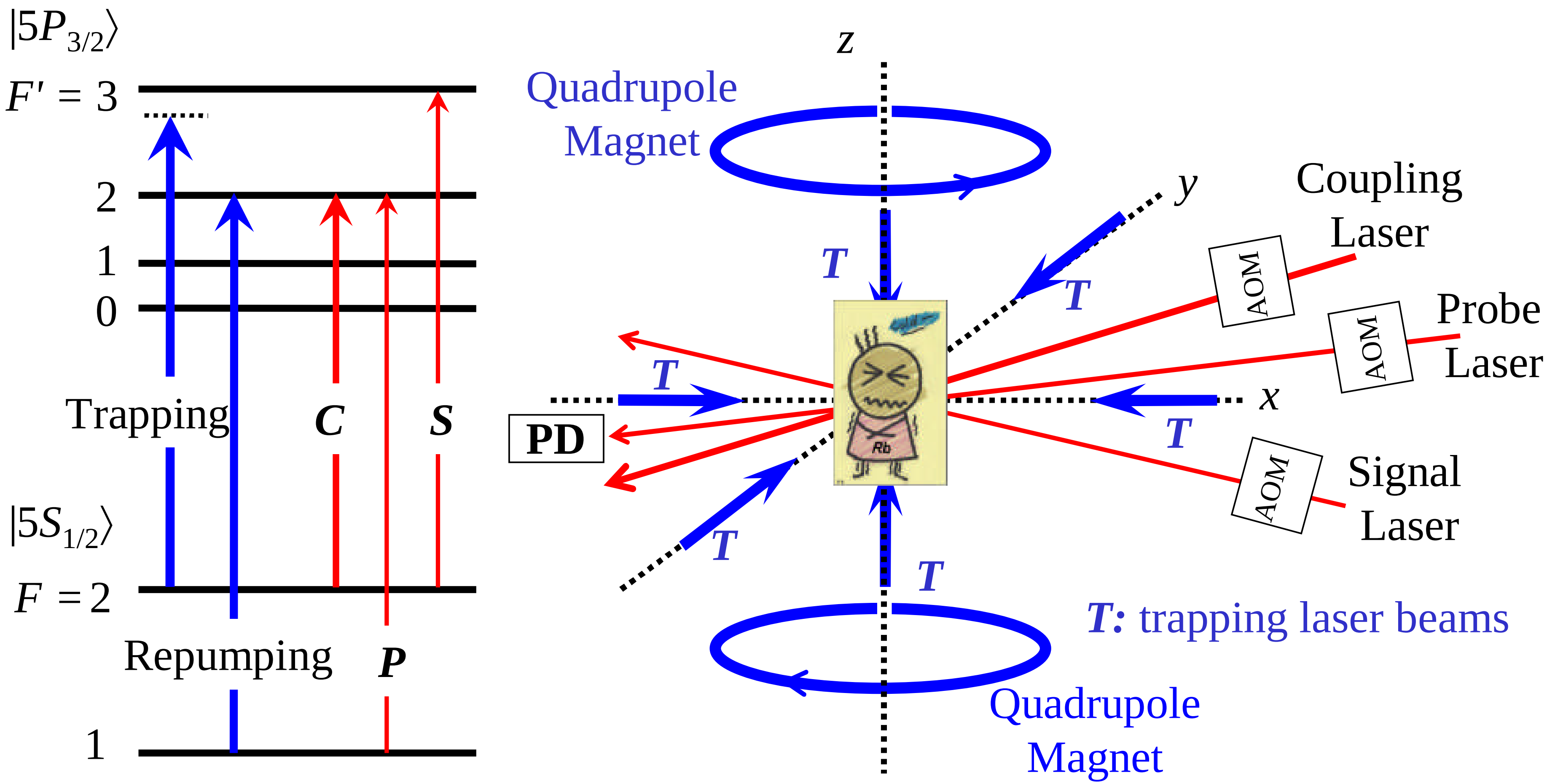
**Ite A. Yu (余怡德)**

Department of Physics
National Tsing Hua University

# Outline

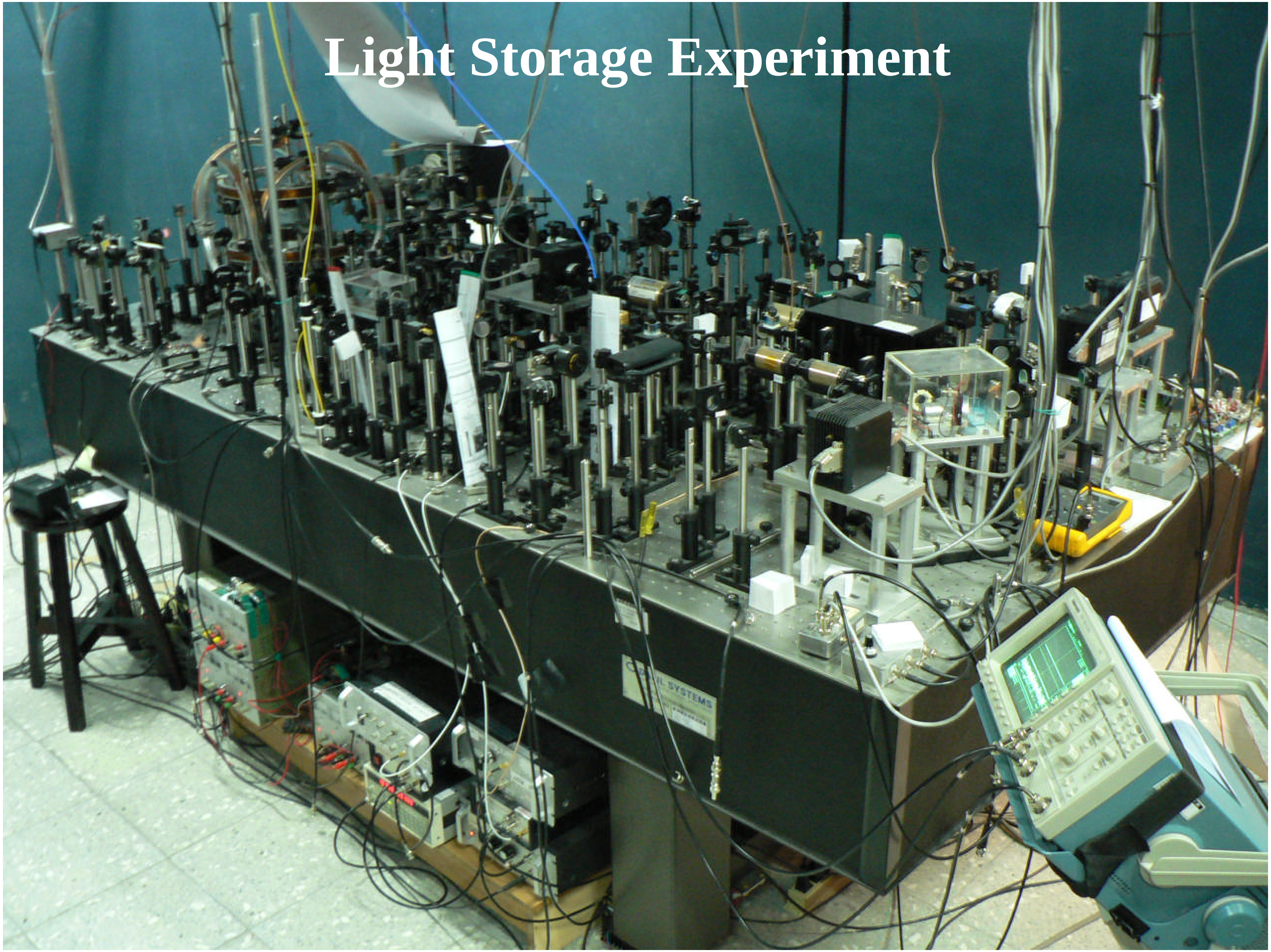
- Experimental setup.
- Electromagnetically induced transparency (EIT), slow light, and storage of light.
- Low-light-level cross-phase modulation and all-optical switching.
- Stationary light pulses.
- Outlook.

# Magneto-Optical Trap (MOT)

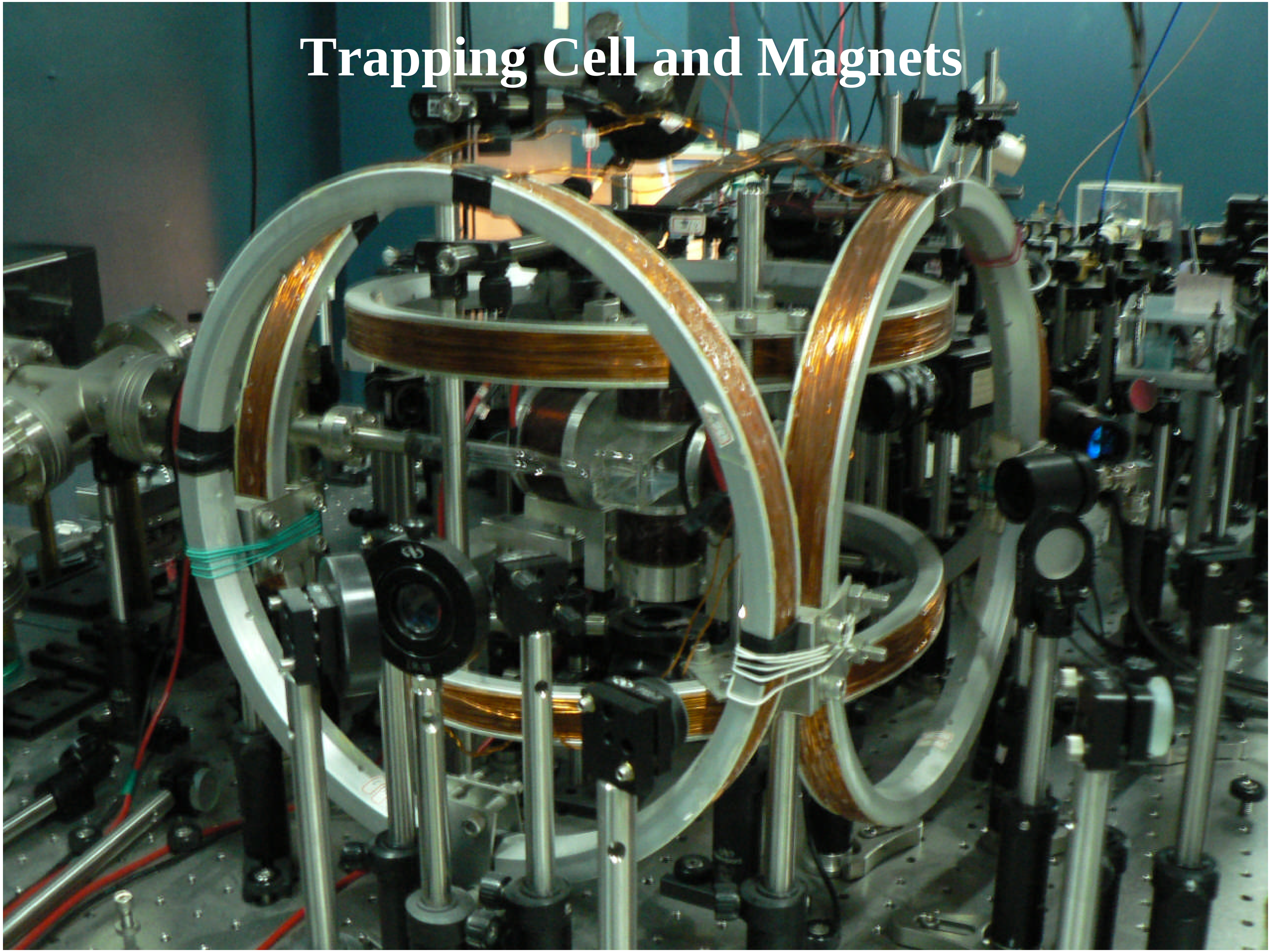



- Typically, we trap $10^9$ atoms at a temperature of about 200 μK in a MOT.
- The probe, coupling, and signal lasers are switched by AOM for the study of the light storage.

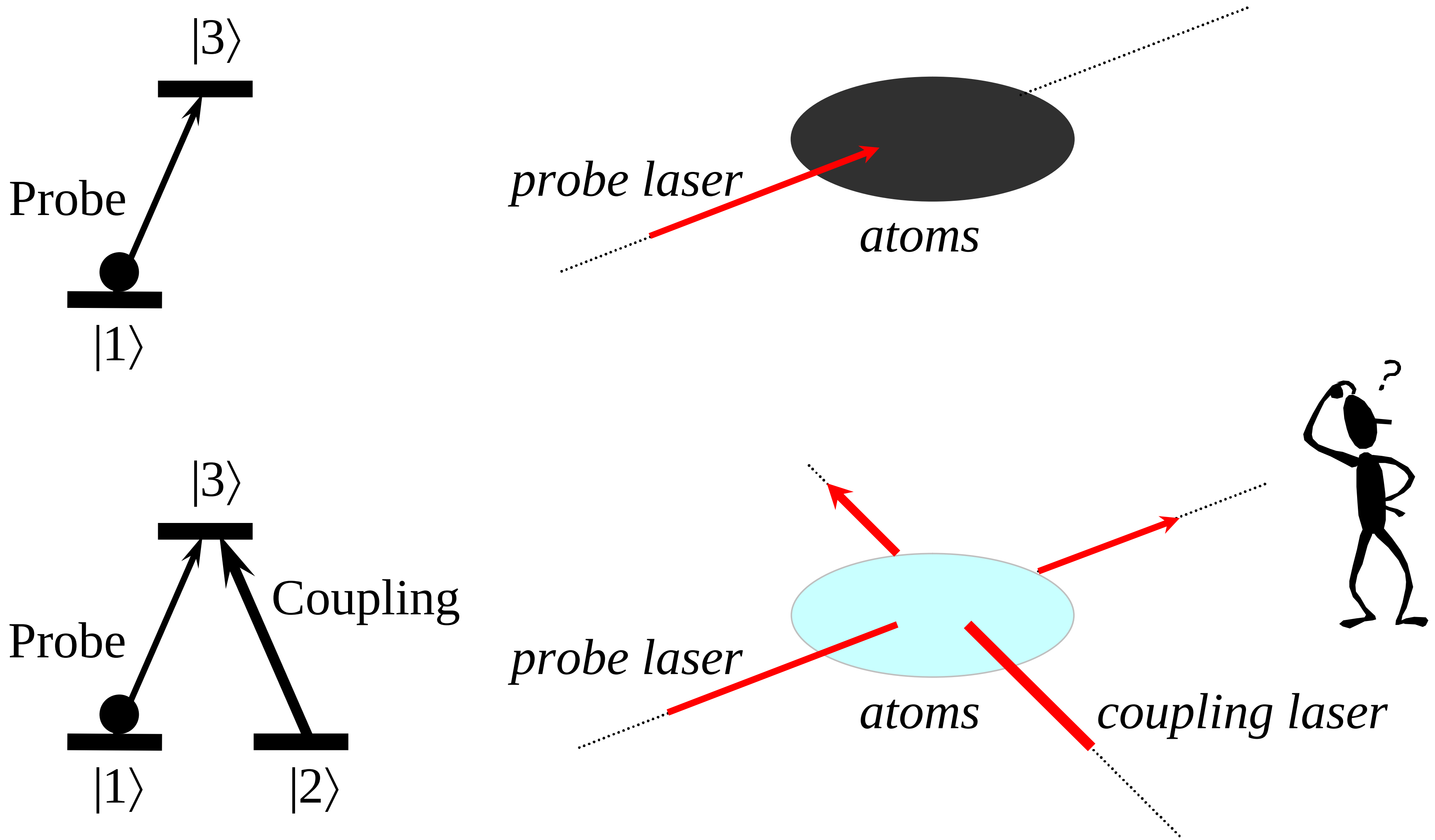
# Light Storage Experiment



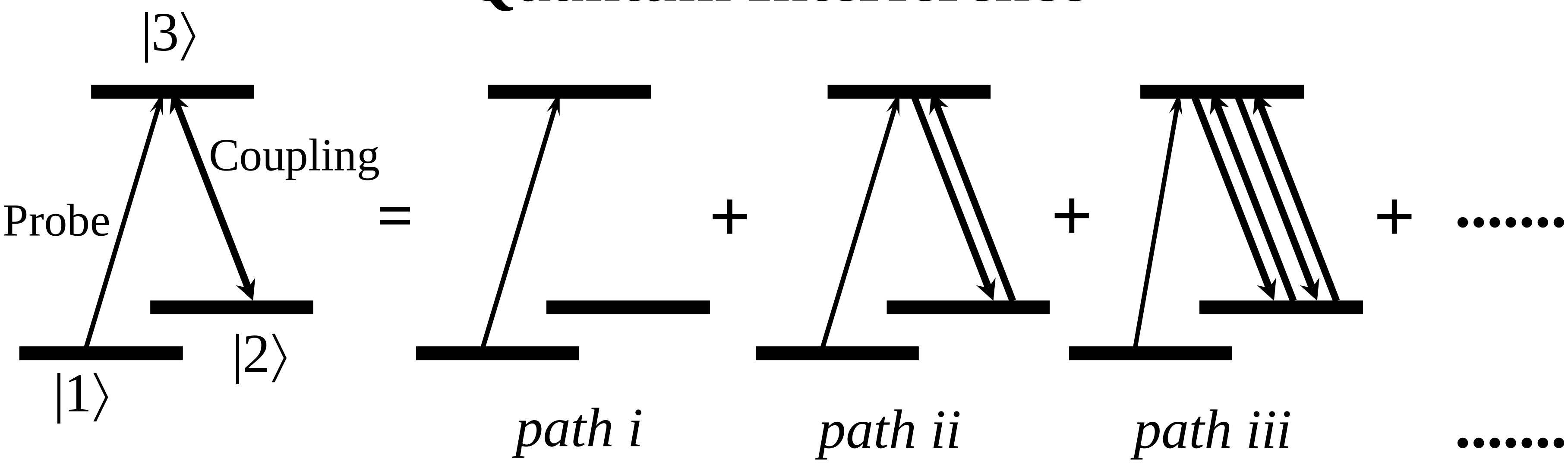
# Trapping Cell and Magnets



# The Phenomenon of
# Electromagnetically Induced Transparency (EIT)



# Quantum Interference




Transition amplitudes: $A_i$ $A_{ii}$ $A_{iii}$ •••••••

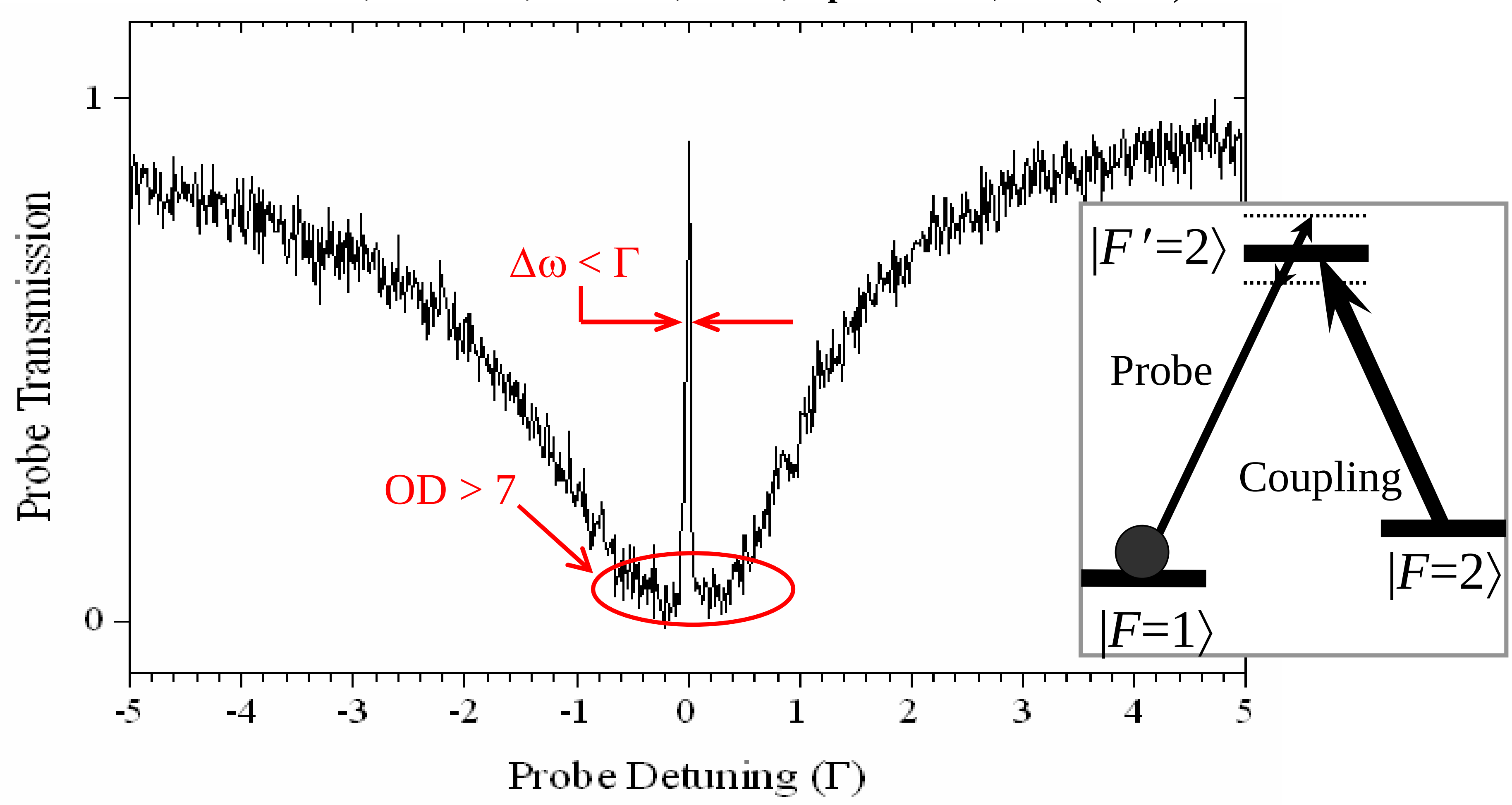
Transition probability of $|1\rangle \rightarrow |2\rangle = |A_i + A_{ii} + A_{iii} + \cdots\cdots|^2$

EIT is the destructive interference between $A_i$ , $A_{ii}$ , $A_{iii}$ , $\cdots\cdots$

$\Rightarrow$ The probe absorption is suppressed.

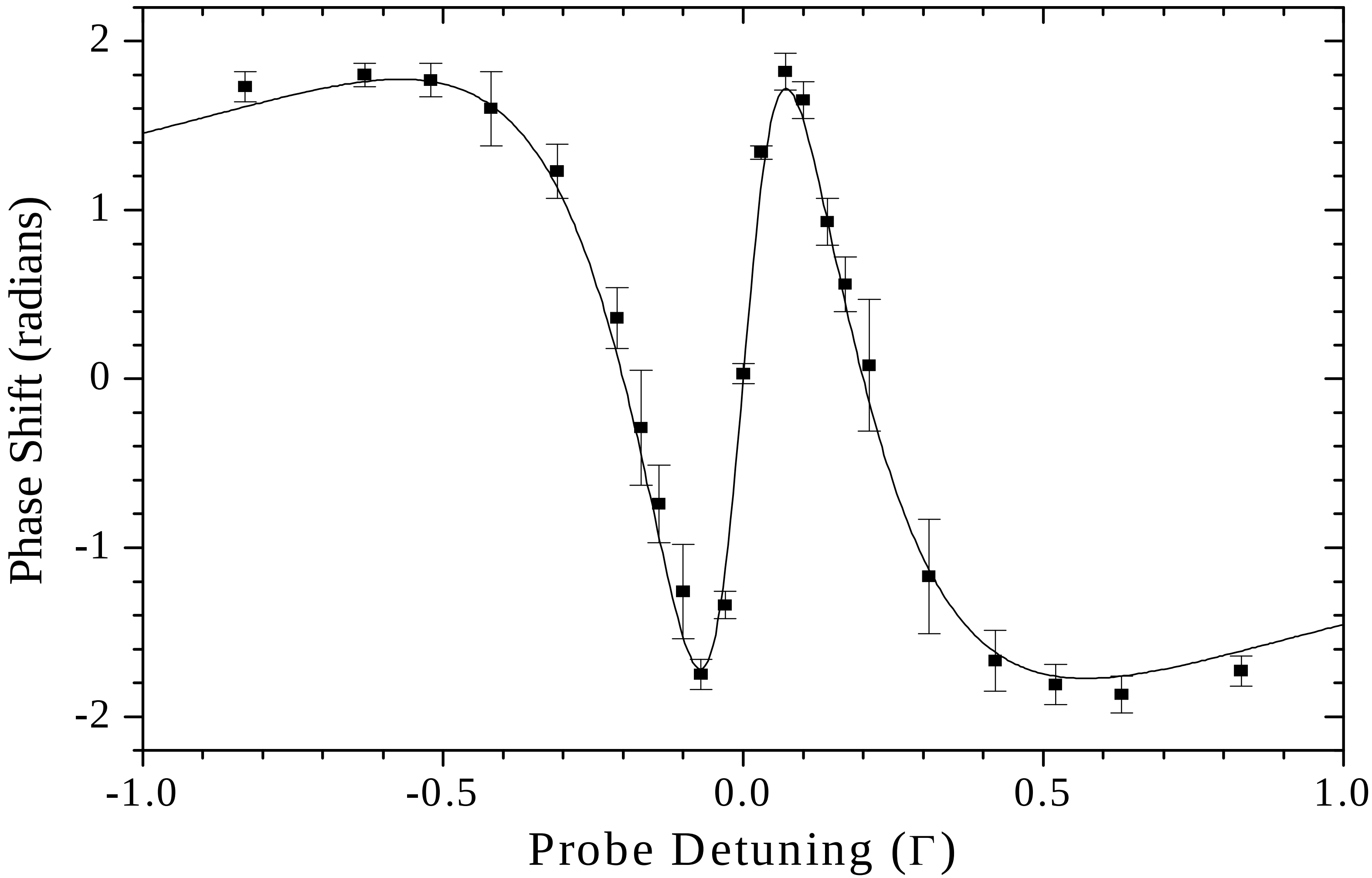
# Narrow-Width and High-Contrast EIT Spectrum

Y. F. Chen, Z. H. Tsai, Y. C. Liu, & *IAY*, **Opt. Lett.** 30, 3207 (2005).




- The optical density (OD) is larger than 7 ($I_{out} = I_{in}\, e^{-OD}$) and probe transmission is less than 0.1% near the resonance.
- Transmission is nearly 100% at the resonance and the transparency window is much narrower than the natural linewidth, Γ.

# Steep Change in Refractive Index




- Due to the refractive index, the probe laser acquires a phase shift after passing through the atoms.
- The EIT effect results in a very large $\omega(dn/d\omega)$.

# Chromatic Dispersion and Slow Light

**narrow-width & high-contrast absorption profile**

$\Downarrow$

**steep change in the refractive index**

$\Downarrow$

**large chromatic dispersion**

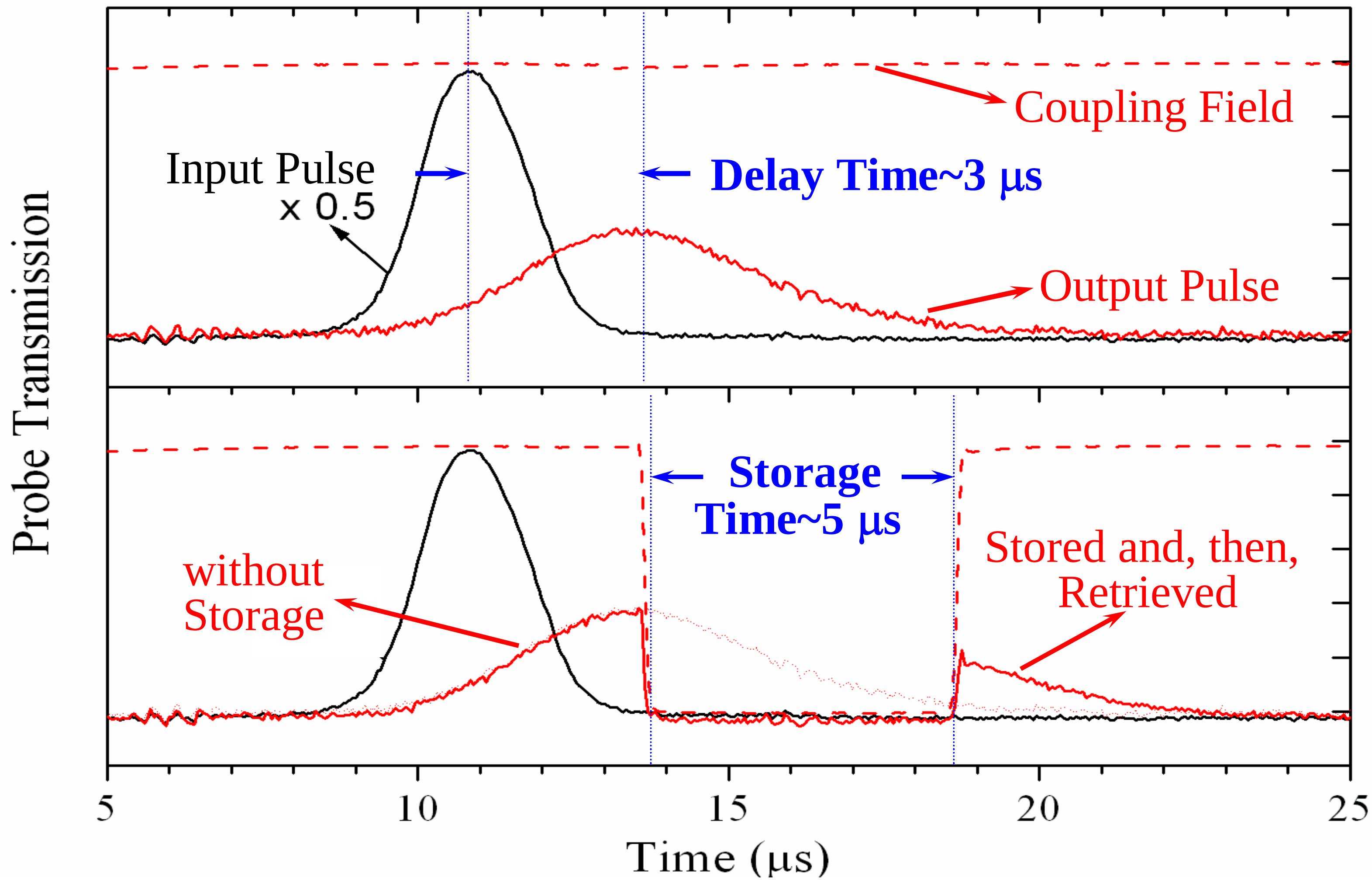
$$k = n\frac{\omega}{c}$$

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

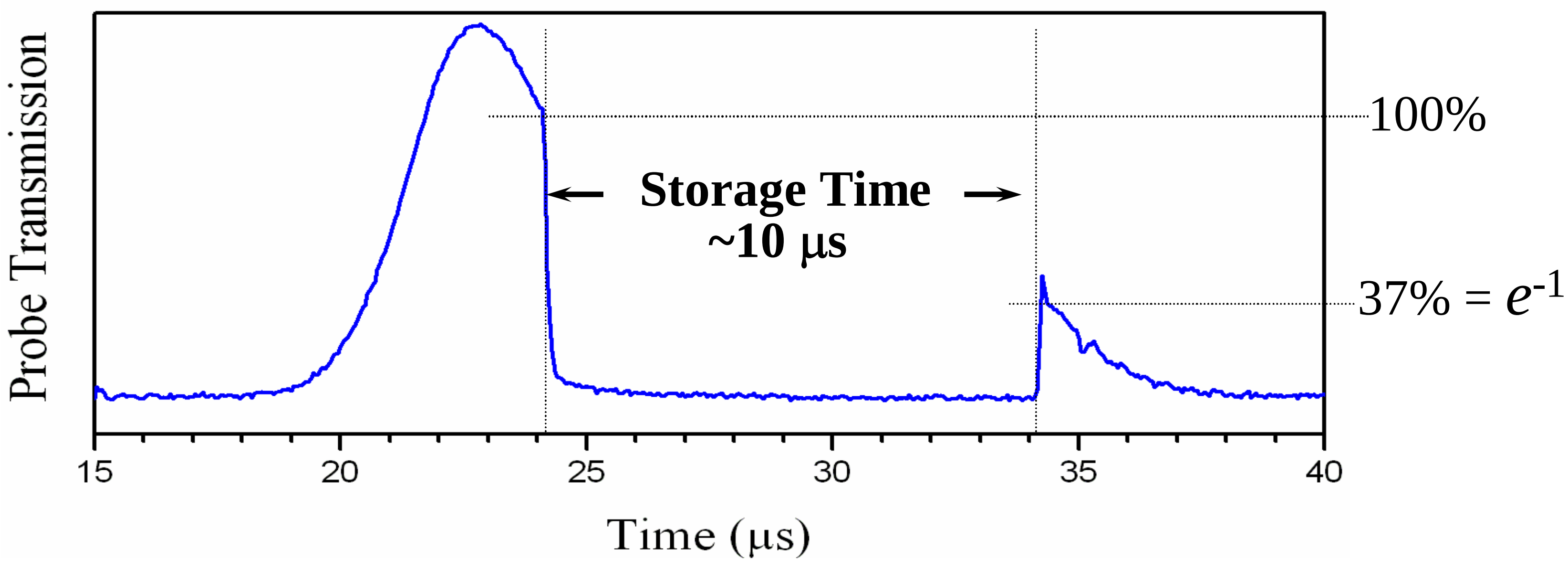
$\omega\frac{dn}{d\omega} \approx 10^6$

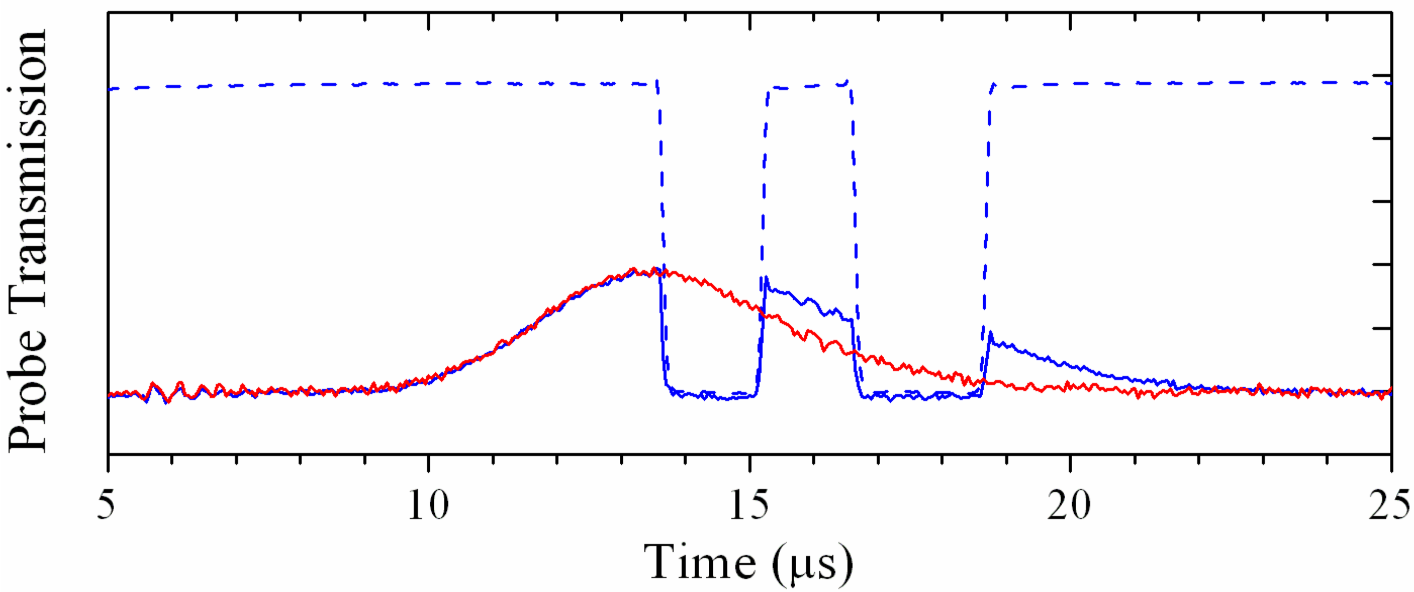
- The group velocity is reduced by six orders of magnitude.
- The dispersion is inversely proportional to the coupling intensity, i.e. $\omega\left(dn/d\omega\right) \propto 1/\Omega_c^2$.

# Slow Light and Storage of Light




- In the constant presence of the coupling, speed of the light pulse ≤ 600 m/s.
- As the second half of the probe pulse remains in the medium, the coupling field is quickly turned off. The gap of ~5 μs in the probe signal demonstrates the storage of the probe pulse.

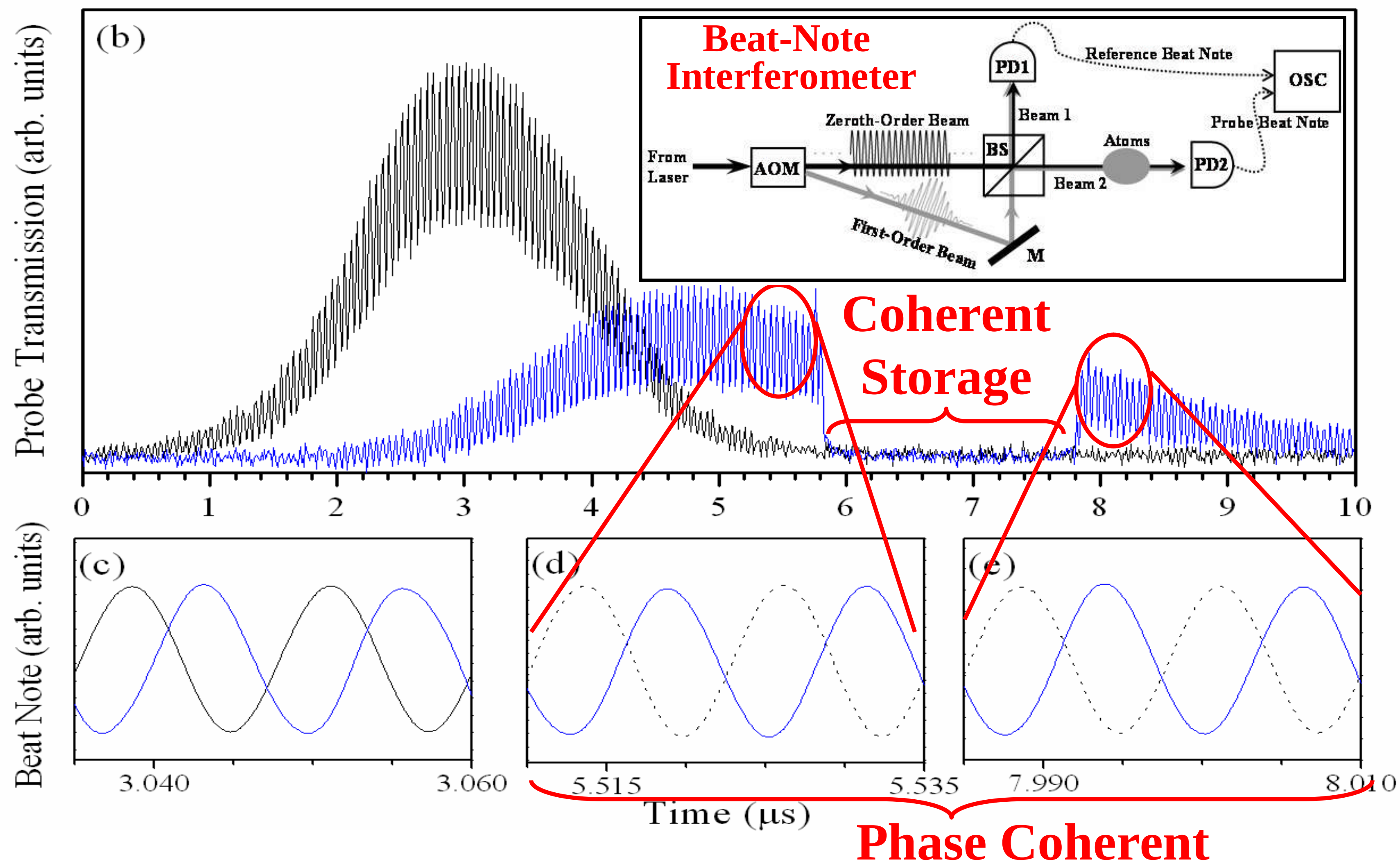



- Storage time ~ 10 μs and slice the probe pulse with the coupling field.
- What is the difference between the EIT storage and the CD or DVD storage?

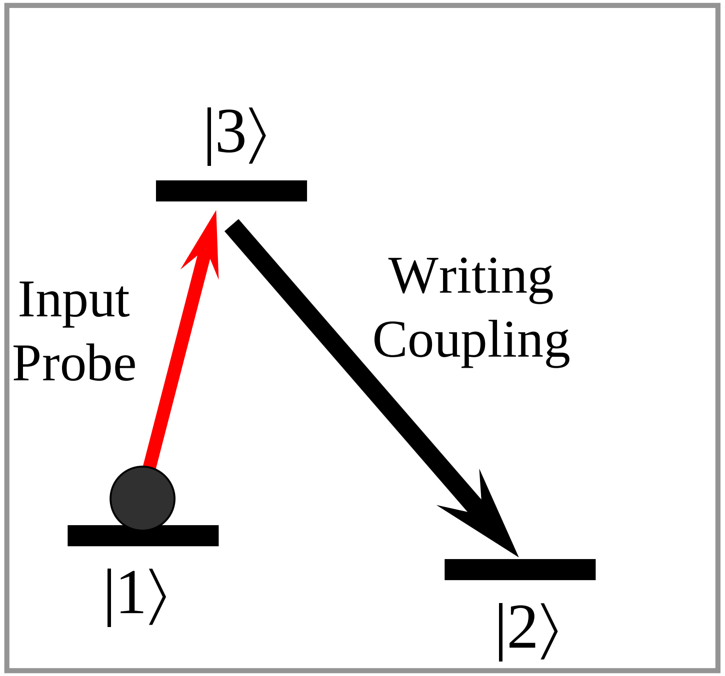
# Phase Coherence of the EIT Storage

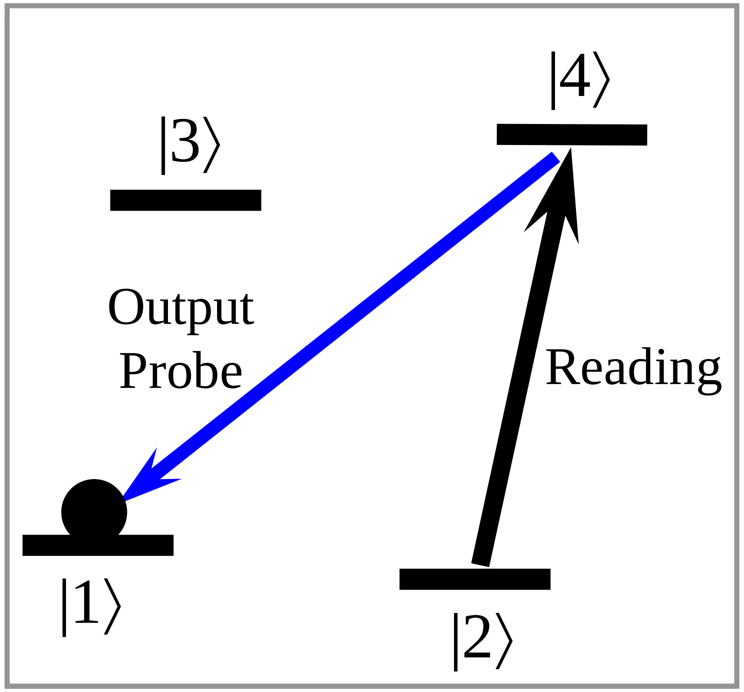
Y. F. Chen, Y. C. Liu, Z. H. Tsai, S. H. Wang, & *IAY*, **PRA** 72, 033812 (2005).
Y. F. Chen, Y. M. Kao, W. H. Lin, & *IAY*, **PRA** 74, 063807 (2006).



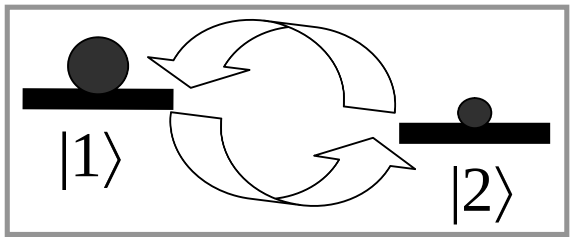

- Developed the **beat-note interferometer** to demonstrate that the stored probe pulse maintains its phase coherence.

# Exchange between EM Wave and Atomic Wave Function




i) The storing process induces the two-photon transition that absorbs probe photons and stimulated emits coupling photons.

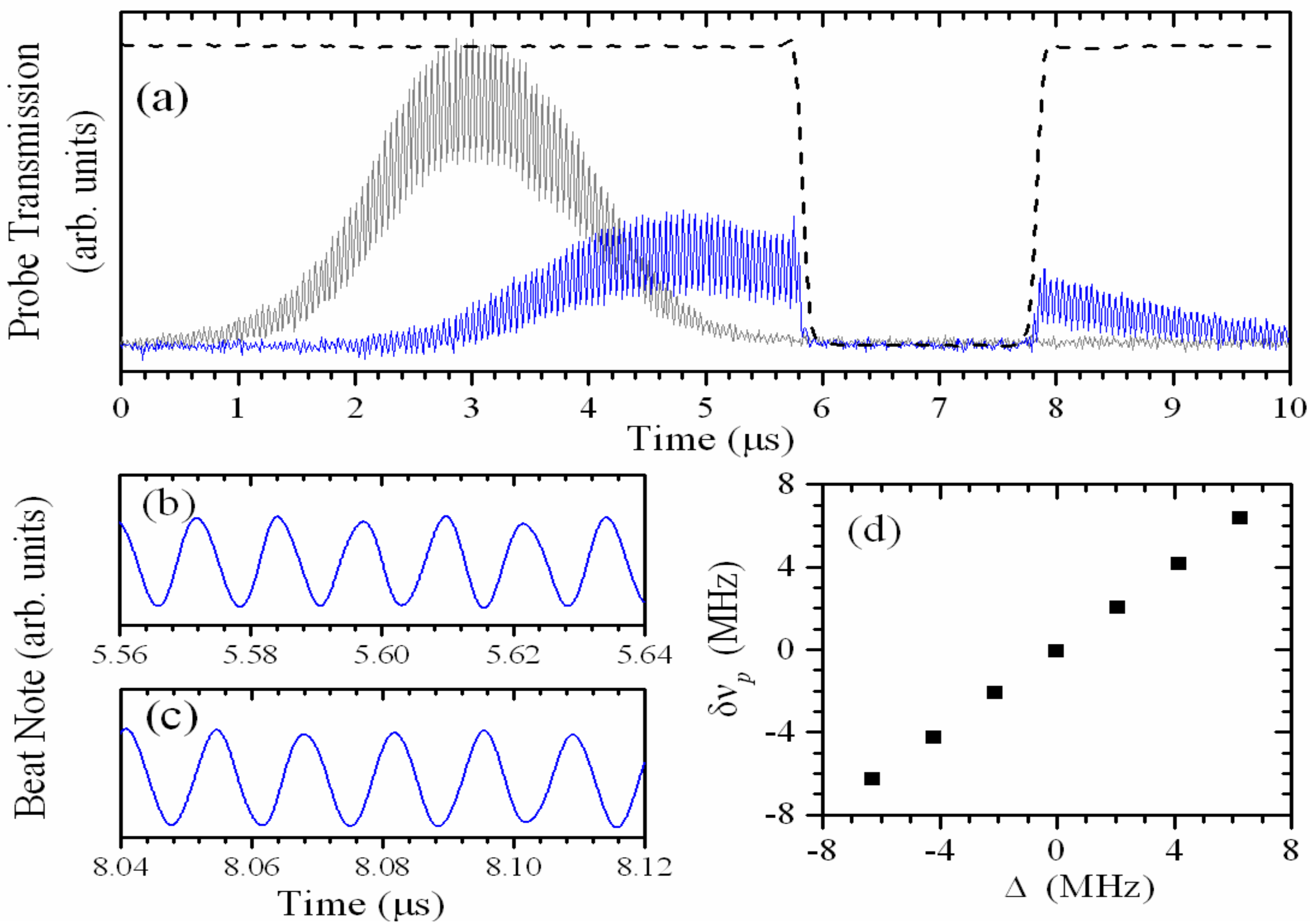



ii) After the coupling is turned off, all the probe photons disappear and the ground-state coherence or spin excitation still remains in the atoms.

iii) The retrieval is the reversal process.

# Manipulate Retrieved Frequency

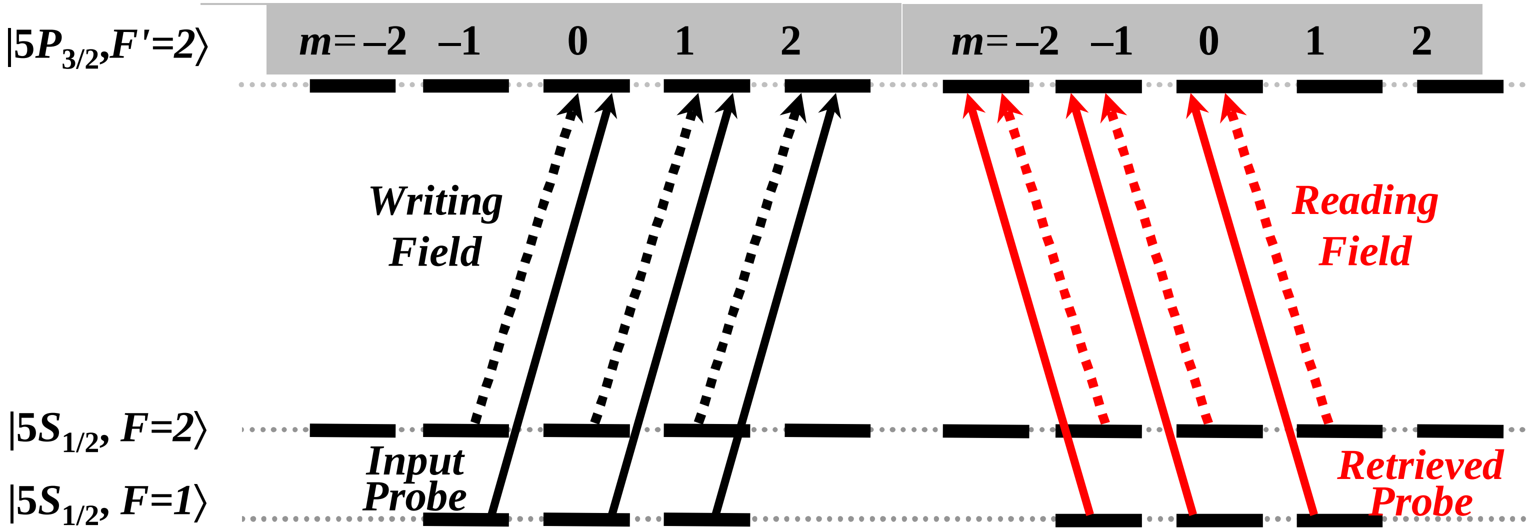
Y. F. Chen, P. C. Kuan, S. H. Wang, C. Y. Wang, & *IAY*, **Opt. Lett.** 31, 3511 (2006).

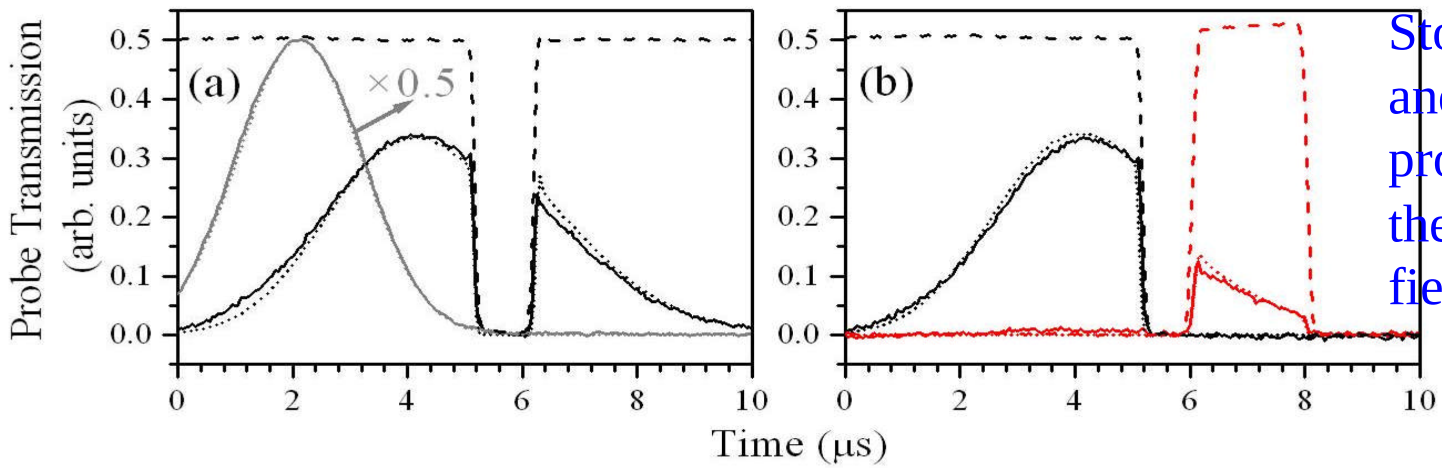



- The first demonstration that the stored and retrieved pulses have different frequencies but maintain phase coherent.

# Manipulate Retrieved Polarization

P. C. Guan, Y. F. Chen, & *IAY*, **PRA** 75, 013812 (2007).
P. C. Guan & *IAY*, **PRA** 76, 033817 (2007).



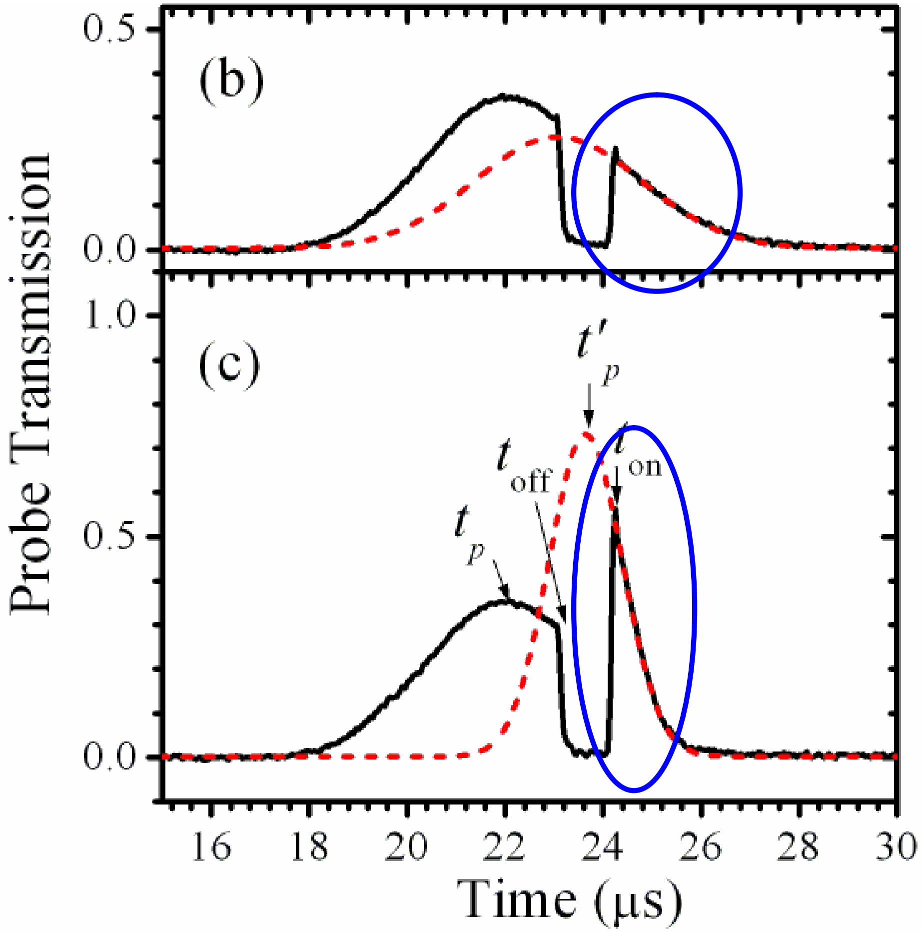



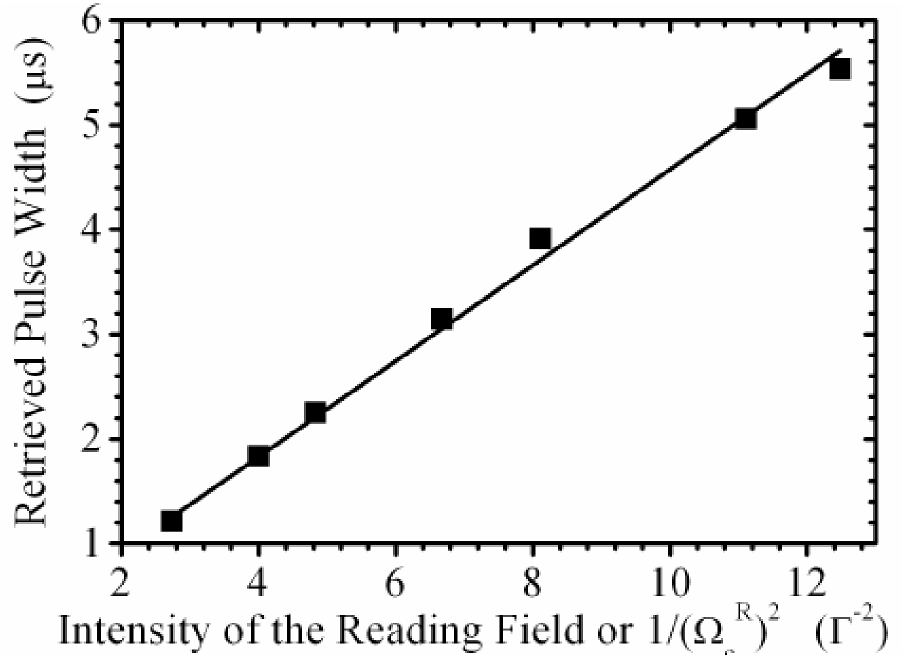

Store a σ+ probe and retrieve a σ− probe by using the σ− reading field.

- The first demonstration that a light pulse is stored with the σ+ polarization and released with the σ− polarization or both polarizations.

# Manipulate Retrieved Pulse Width

Y. F. Chen, S. H. Wang, C. Y. Wang, & *IAY*, **PRA** 72, 053803 (2005).

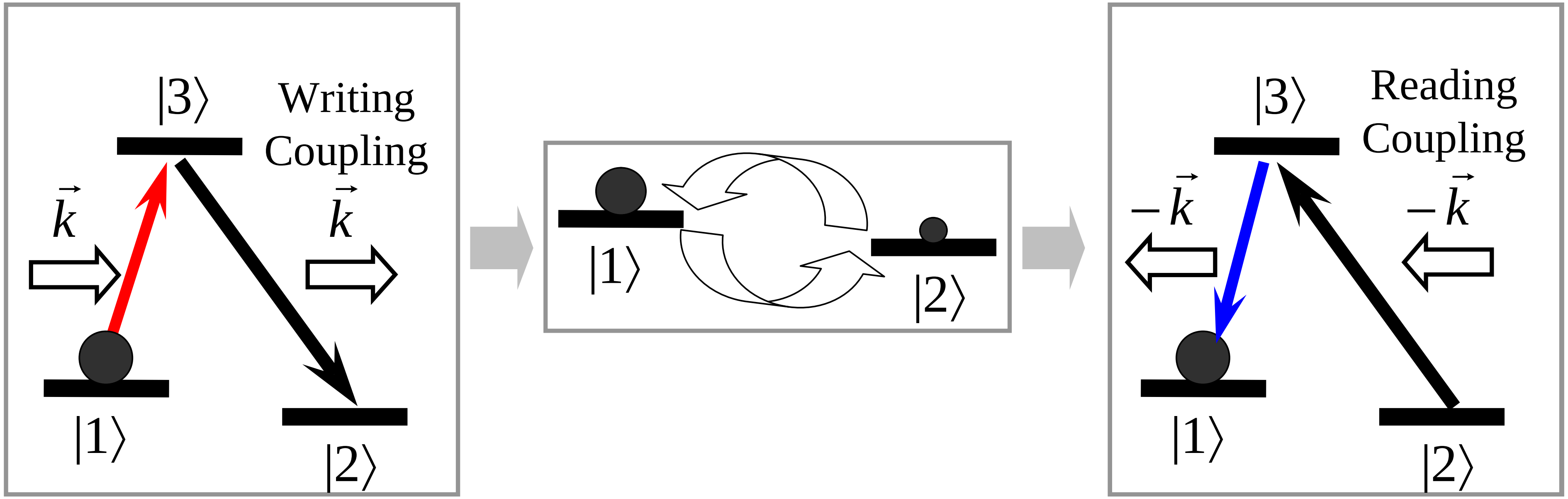



- Stronger $I_c$ retrieves a larger $I_{p0}$ and a narrower $\tau_p$. Energy is the same.
- $\tau_p \propto 1/ I_c$

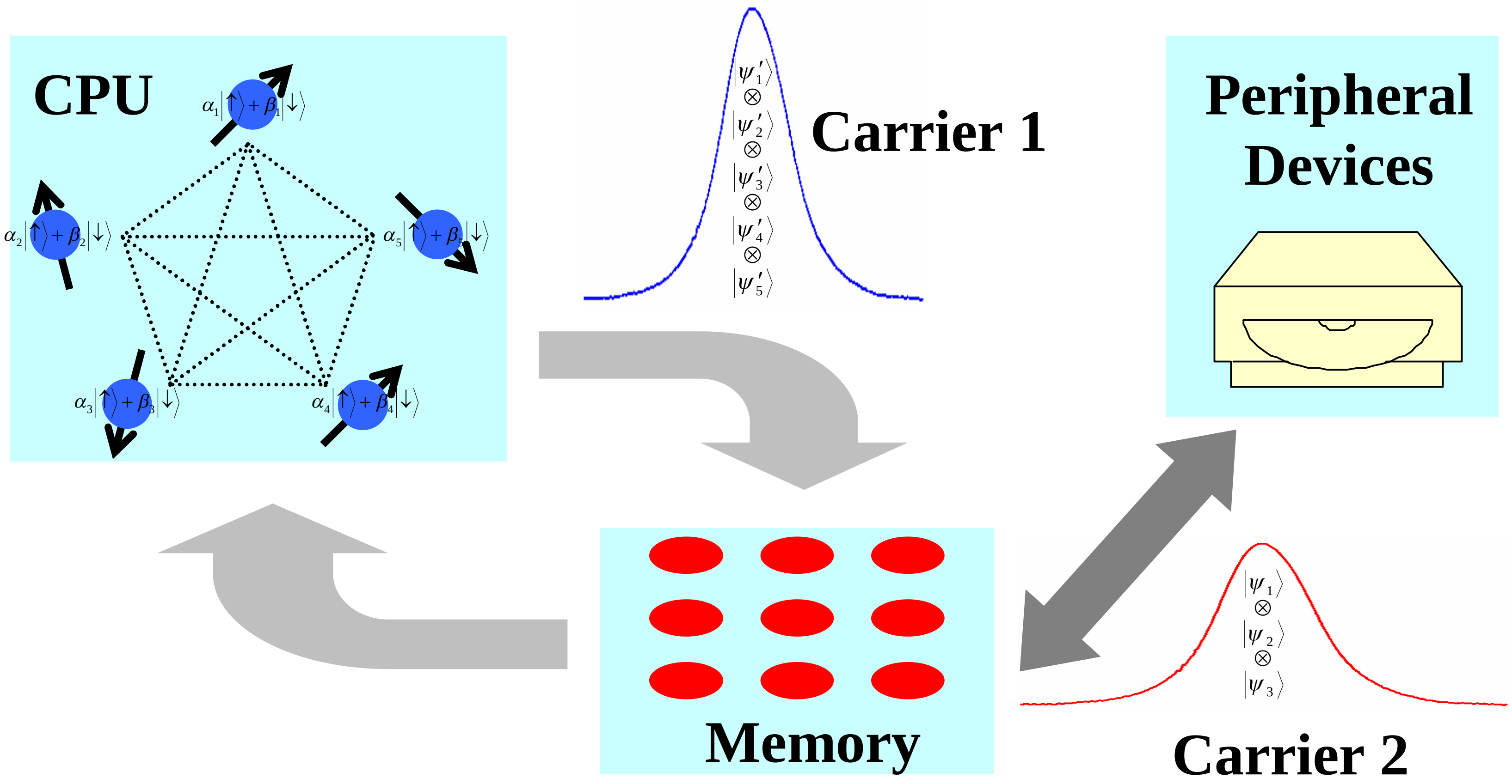
- The first demonstration of manipulating the retrieved pulse width. There is no phase jitter or jump caused by the manipulation of retrieval.

# Manipulation of Retrieval




- The light storage based on the EIT effect provides the method for exchange of wave functions between photons and atoms.
- The stored atomic coherence is equivalent to the probe pulse.
- The retrieved probe pulse and the reading coupling field always maintain the two-photon resonance and the phase matching.
- Photons as the information carrier can change properties, but the carried information is intact.
- Nevertheless, **light is not actually stopped in the medium.**

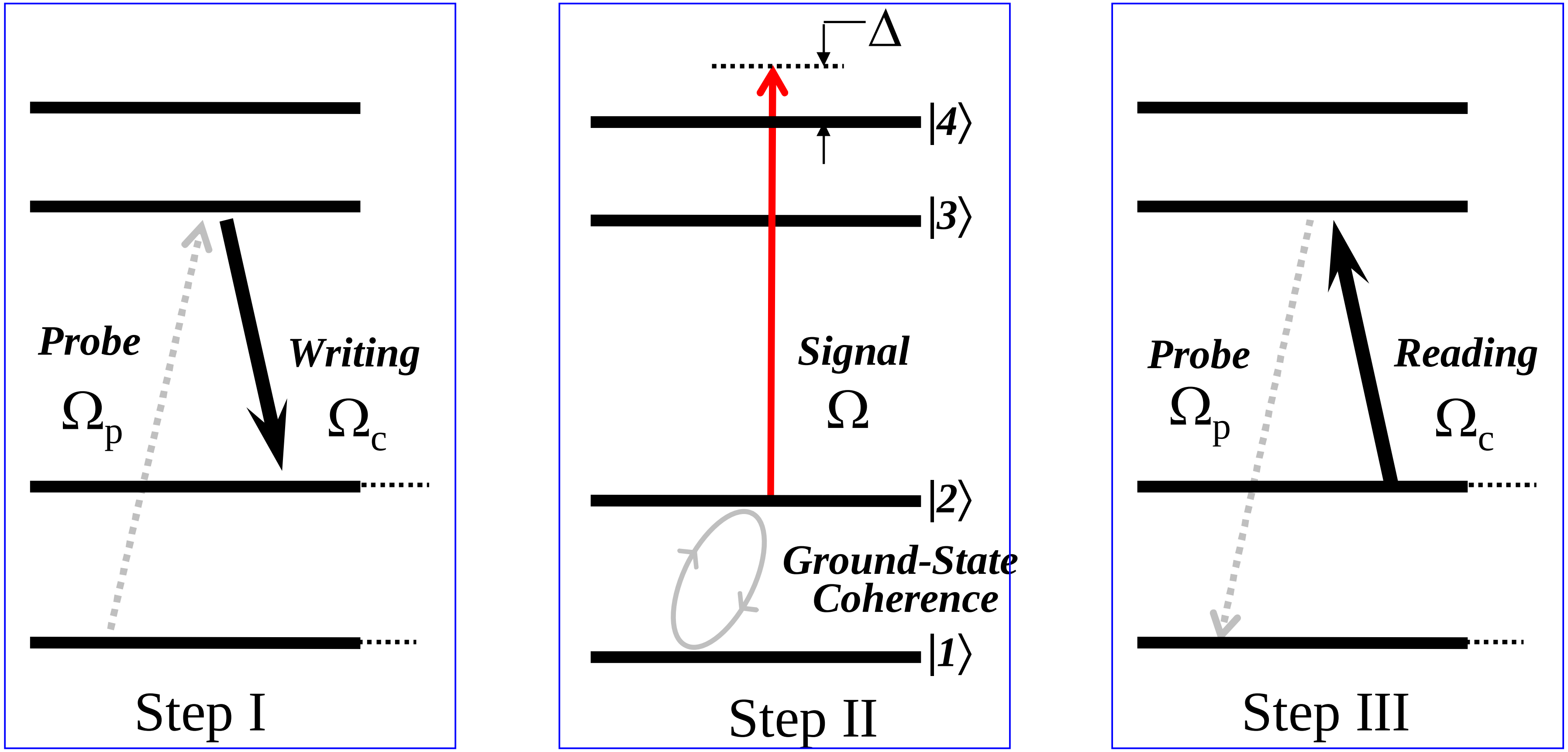
# A Quantum Computer




- Light is an ideal carrier of quantum information or wave functions, because of being inert to the environment during the information transportation.
- A quantum computer may consist of different types of quantum devices made by various kinds of media. The light storage can bridge different quantum devices, each of which only interacts with light of specific properties.

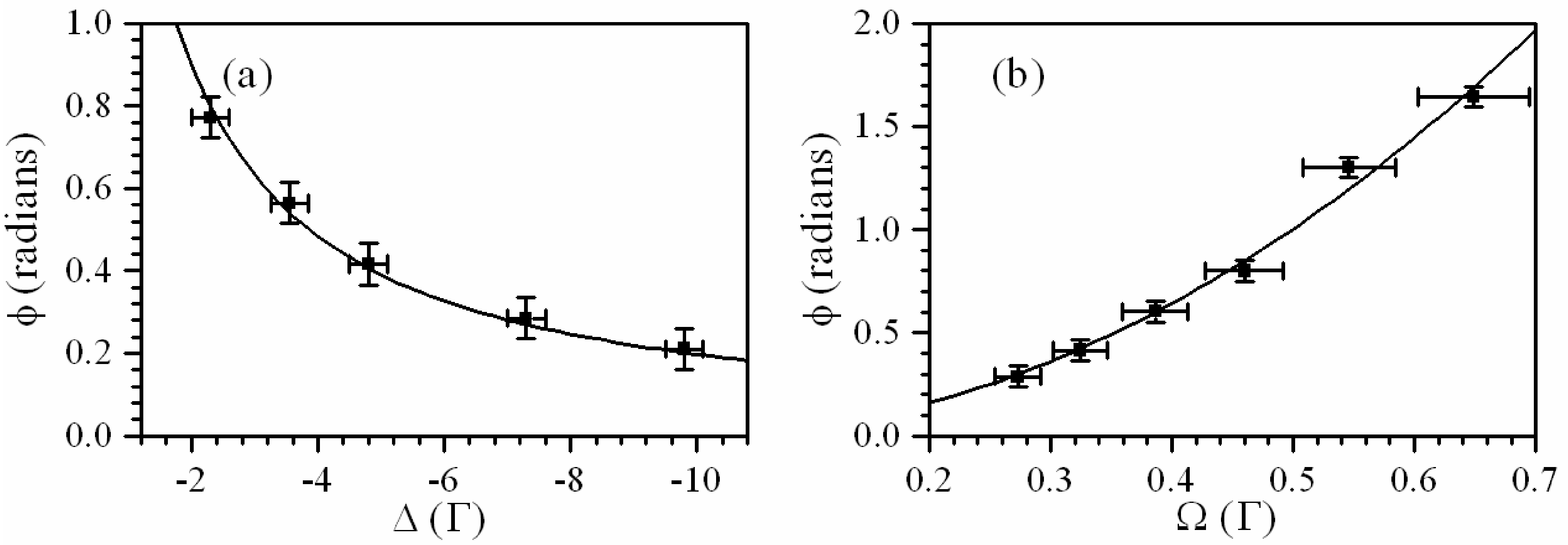
# Cross-Phase Modulation Based on Light Storage

Y. F. Chen, C. Y. Wang, S. H. Wang, and *IAY*, **PRL** 96, 043603 (2006).



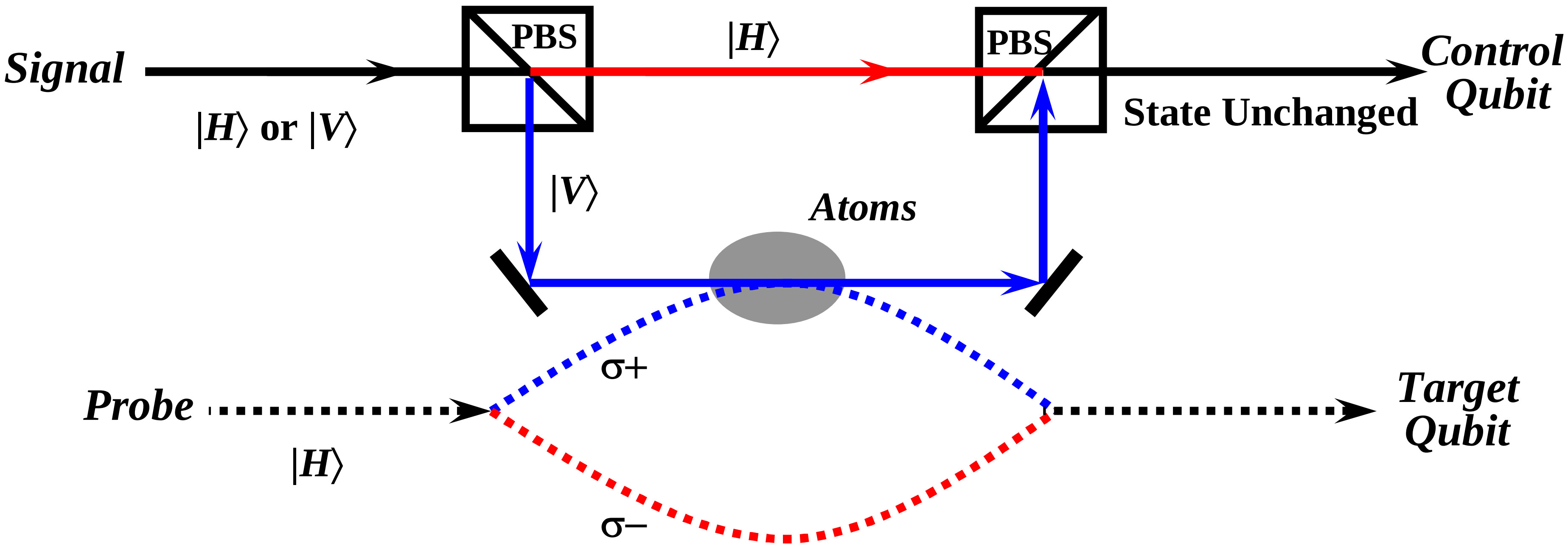

- During the storage, a signal pulse induces the AC Stark shift and changes the frequency and, hence, the phase of the ground-state coherence.
- The stored coherence is equivalent to the probe pulse. Therefore, the phase of the retrieved probe pulse is also modulated.

$$\Phi = -\frac{\Omega^2 \Delta}{\Gamma'^2 + 4\Delta^2}\tau$$




- A phase shift of 44° and energy transmission of 65% is obtained at 6 photons per $\lambda^2/(2\pi)$.
- Phase shifts of the order of $\pi$ with single signal photons can be achievable.
- Quantum nondemolition measurements, quantum phase gates, entangled photon pairs.

# Quantum Logic Gates

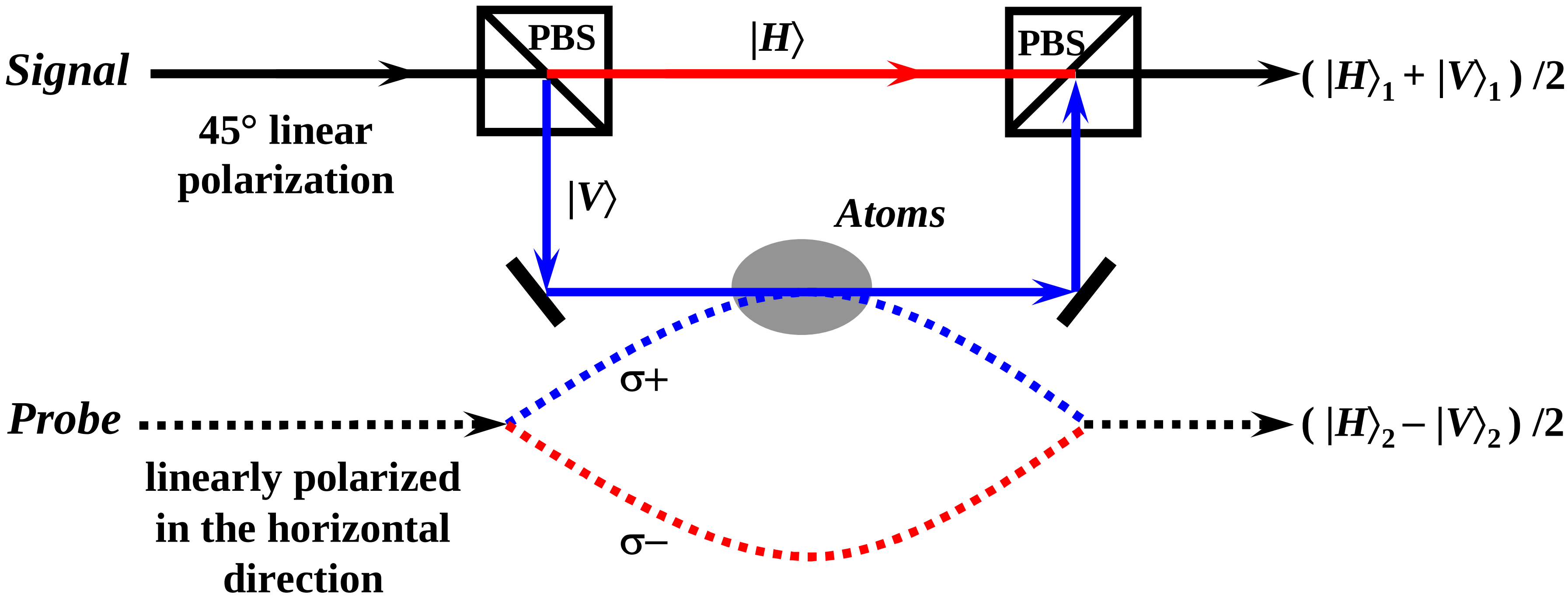



$\sigma+ = ( |H\rangle + i|V\rangle )/2$ **phase shift of π** ⇒ $\sigma+ = -( |H\rangle + i|V\rangle )/2$

$\sigma- = ( |H\rangle - i|V\rangle )/2$

$$|H\rangle = |0\rangle \text{ and } |V\rangle = |1\rangle \quad \begin{cases} \text{Control} = |0\rangle \Rightarrow \text{Target} = \text{Target} \\ \text{Control} = |1\rangle \Rightarrow \text{Target} = \overline{\text{Target}} \end{cases}$$

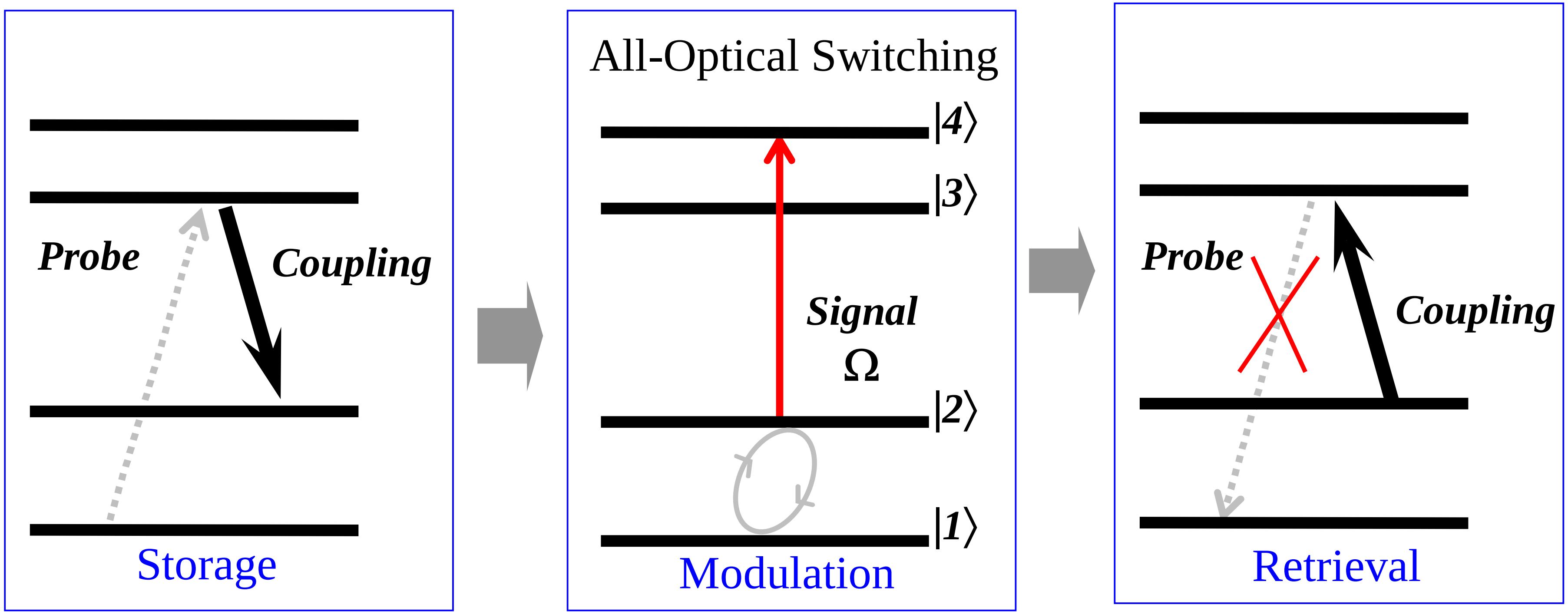
# Entangled Photon Pairs




$$( |H\rangle_1 |V\rangle_2 - |V\rangle_1 |H\rangle_2 ) /2$$

# All-Optical Switching via Light Storage

C. Y. Wang, Y. F. Chen, S. C. Lin, W. H. Lin, P. C. Kuan, & *IAY*, **Opt. Lett.** 31, 2350 (2006).
W. H. Lin, W. T. Liao, C. Y. Wang, Y. F. Lee, & *IAY*, **PRA** 78, 033807 (2008).




$$\text{Attenuation} = \exp\left[-\Omega^2\tau/(2\Gamma)\right]$$

- An on-off ratio of 10 dB was achieved in the all-optical switching.
- Single photon switched by another is achievable.

# Motivation of Stationary Light Pulses (SLPs)

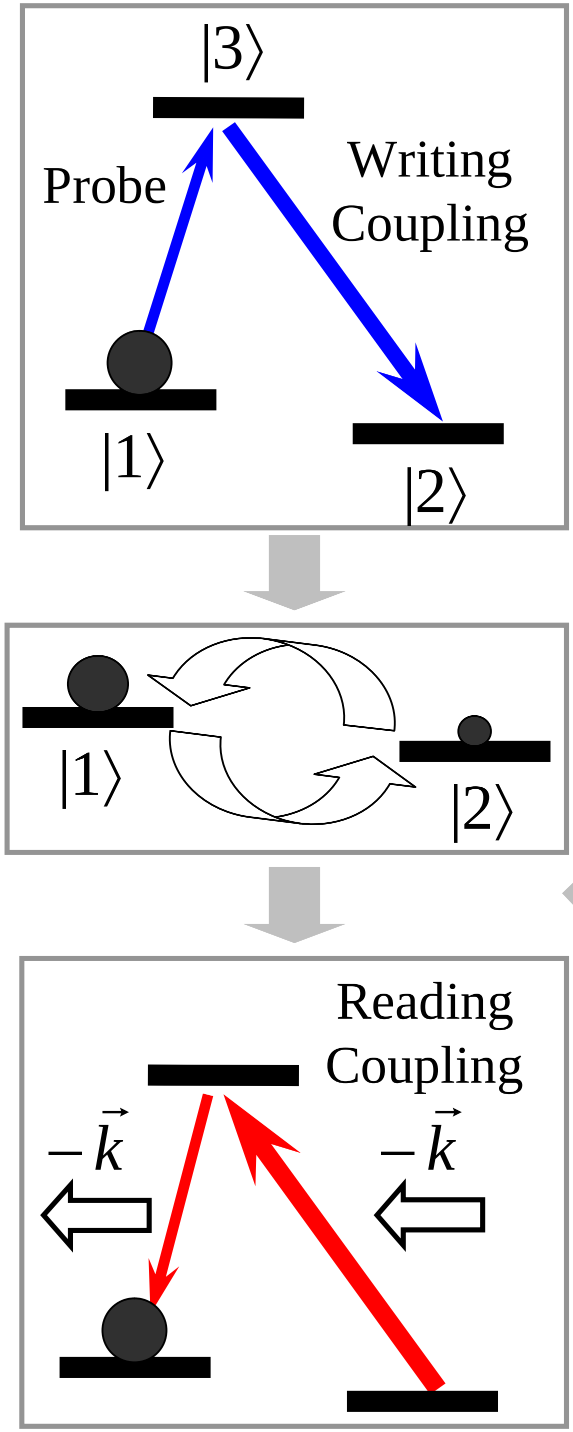
Cross-Phase Modulation (XPM): $\Phi = -\Omega^2 \tau \dfrac{\Delta}{\Gamma^2 + 4\Delta^2}$

All-Optical Switching: $\text{attenuation} = \exp\left[-\Omega^2 \tau / (2\Gamma)\right]$

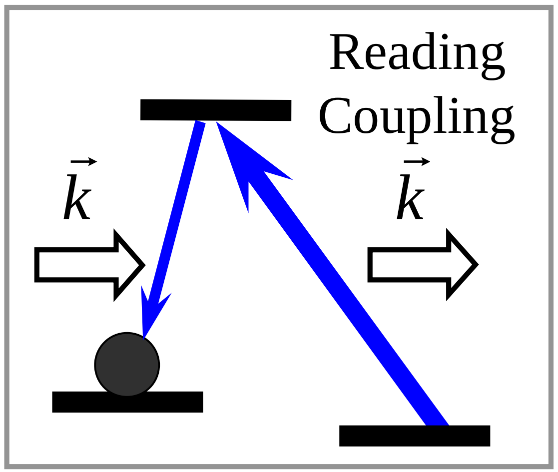
- $\Omega^2$ is proportional to the intensity of the signal pulse and $\tau$ is the interaction time between the light and the atoms (and, equivalently, is the signal pulse width).
- A shorter pulse width does not help the XPM or switching efficiency, because $\Omega^2\tau$ is still fixed at a given photon energy.
- Nevertheless, $\Omega^2\tau$ can be greatly enhanced or $\tau$ is not limited to the pulse width by making the light pulse motionless, i.e., a stationary light pulse.
- Single-photon XPM and all-optical switching become more feasible.

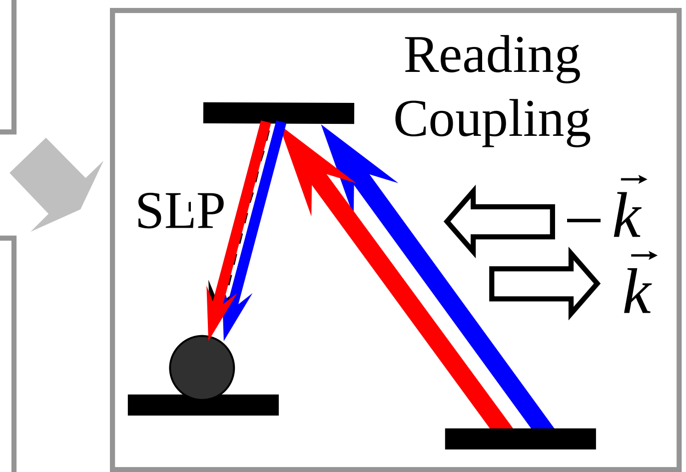
# Stationary Light Pulses (SLPs)

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




The SLP is formed by simultaneously switching on the forward and backward coupling fields of equal intensities to retrieve the stored atomic coherence.



# Mechanism of SLPs

**Nature** 426, 638 (2003).

## Stationary pulses of light in an atomic medium

**M. Bajcsy[1,2], A. S. Zibrov[1,3,4] & M. D. Lukin[1]**

[1]*Physics Department,* [2]*Division of Engineering and Applied Sciences, Harvard University,* [3]*Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA*
[4]*Lebedev Institute of Physics, Moscow, 117924 Russia*

Physical processes that could facilitate coherent control of light propagation are under active exploration[1–5]. In addition to their fundamental interest, these efforts are stimulated by practical possibilities, such as the development of a quantum memory for photonic states[6–8]. Controlled localization and storage of

beam[14–16]. The atomic coherence can be converted into a stationary photonic excitation if the medium is illuminated simultaneously by forward and backward control beams. Specifically, if the two create a standing wave pattern, the EIT suppresses the signal absorption everywhere but in the nodes of the standing wave, resulting in a sharply peaked, periodic modulation of the atomic absorption for the signal light (Fig. 1b). Illumination by these beams also results in partial conversion of the stored atomic spin excitation into sinusoidally modulated signal light, but the latter cannot propagate in the medium owing to Bragg reflections off the sharp absorption peaks, resulting in vanishing group velocity of the signal pulse. Only after one of the control beams is turned off does the pulse acquire a finite velocity and can thus leave the medium in the direction of the remaining control beam.

To quantify these effects theoretically, we consider the interaction of atoms with resonant optical fields, represented by plane waves. We decompose the signal field into components propagating in the forward and backward directions along the $z$ axis with wavevectors $\pm k$ and slowly varying amplitudes $E_{\pm}$. Following refs 13 and 18, we introduce two components $\Psi_{\pm}$ of a coupled excitation of light and an atomic spin wave ('dark-state polariton') corresponding to forward and backward signal fields, respectively. In the experimentally relevant case of small group velocities, the polariton components are represented by $\Psi_{\pm} = g\sqrt{N}E_{\pm}/\Omega_{\pm}$, where $g$ is the atom–





- Lukin's group proposed and demonstrated the stationary pulse in a hot atomic gas.
- Retrieve the stored atomic coherence by forward and backward coupling fields.
- The two couplings fields with equal intensities form a standing wave whose nodes and anti-nodes create periodic modulation of atomic absorption, i.e. a Bragg grating.
- The Bragg grating similar to a photonic bandgap material results in vanishing group velocity of the probe pulse.

# Equations for SLPs

Coupling $\rightarrow \Omega_c^+ e^{ik_c^+ z} + \Omega_c^- e^{-ik_c^- z}$

Probe $\rightarrow \Omega_p^+ e^{ik_p^+ z} + \Omega_p^- e^{-ik_p^- z}$

Optical Coherence $\rightarrow \rho_{31}^+ e^{ik_p^+ z} + \rho_{31}^- e^{-ik_p^- z}$

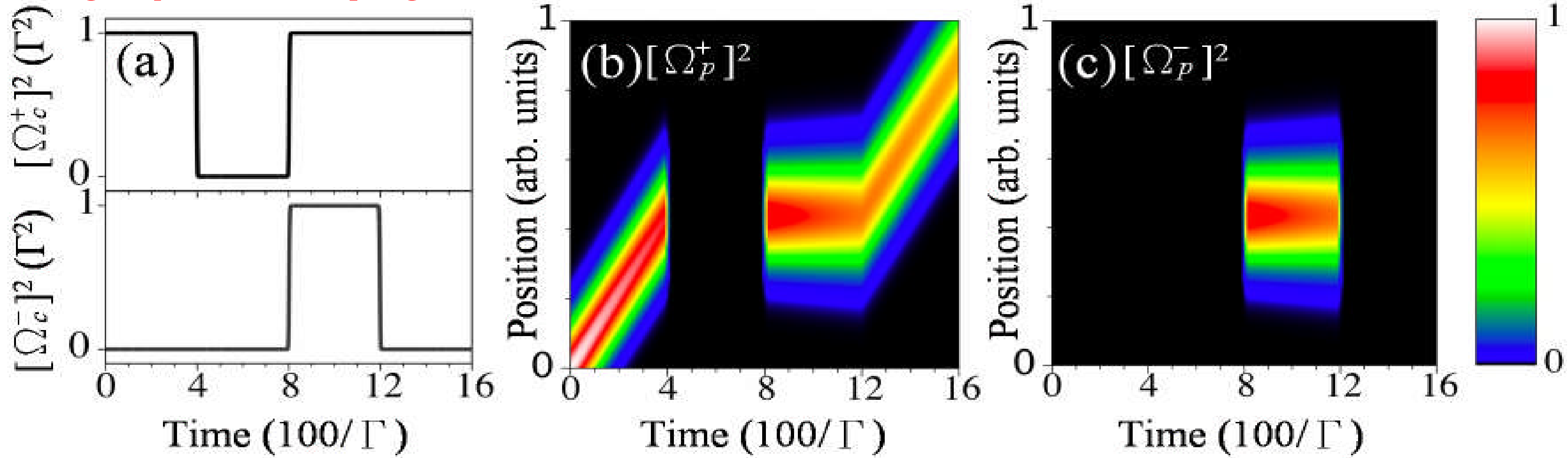
Assume $k_c^+ \approx k_p^+ ;\; k_c^- \approx k_p^-$

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

$$
\left\{
\begin{aligned}
\frac{\partial \rho_{21}}{\partial t} &= \frac{i}{2}(\Omega_c^+)^* \rho_{31}^+ + \frac{i}{2}(\Omega_c^-)^* \rho_{31}^- - \gamma \rho_{21}, \\
\frac{\partial \rho_{31}^+}{\partial t} &= \frac{i}{2}\Omega_p^+ + \frac{i}{2}\Omega_c^+ \rho_{21} - \frac{\Gamma}{2}\rho_{31}^+, \\
\frac{\partial \rho_{31}^-}{\partial t} &= \frac{i}{2}\Omega_p^- + \frac{i}{2}\Omega_c^- \rho_{21} - \frac{\Gamma}{2}\rho_{31}^-, \\
\frac{1}{c}\frac{\partial \Omega_p^+}{\partial t} + \frac{\partial \Omega_p^+}{\partial z} &= i\frac{\alpha\Gamma}{2L}\rho_{31}^+, \\
\frac{1}{c}\frac{\partial \Omega_p^-}{\partial t} - \frac{\partial \Omega_p^-}{\partial z} &= i\frac{\alpha\Gamma}{2L}\rho_{31}^-.
\end{aligned}
\right.
$$

Timing Sequence of Coupling Fields

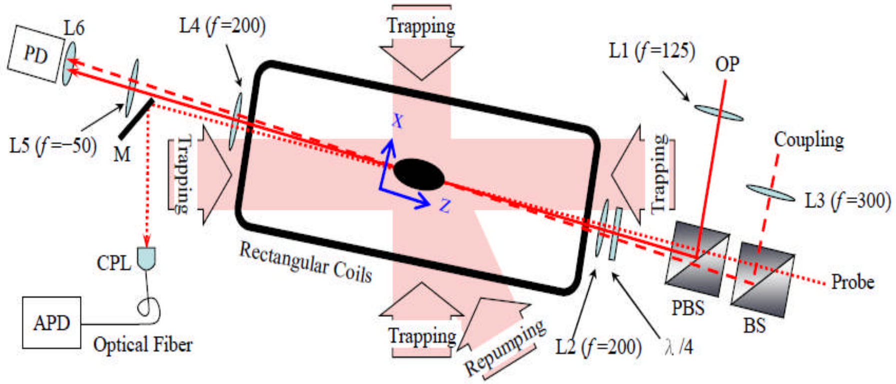
Forward and Backward Probe Pulses as Functions of *z* and *t*

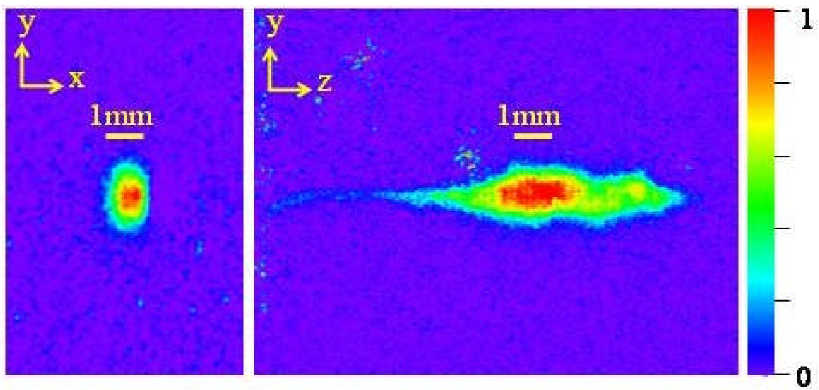


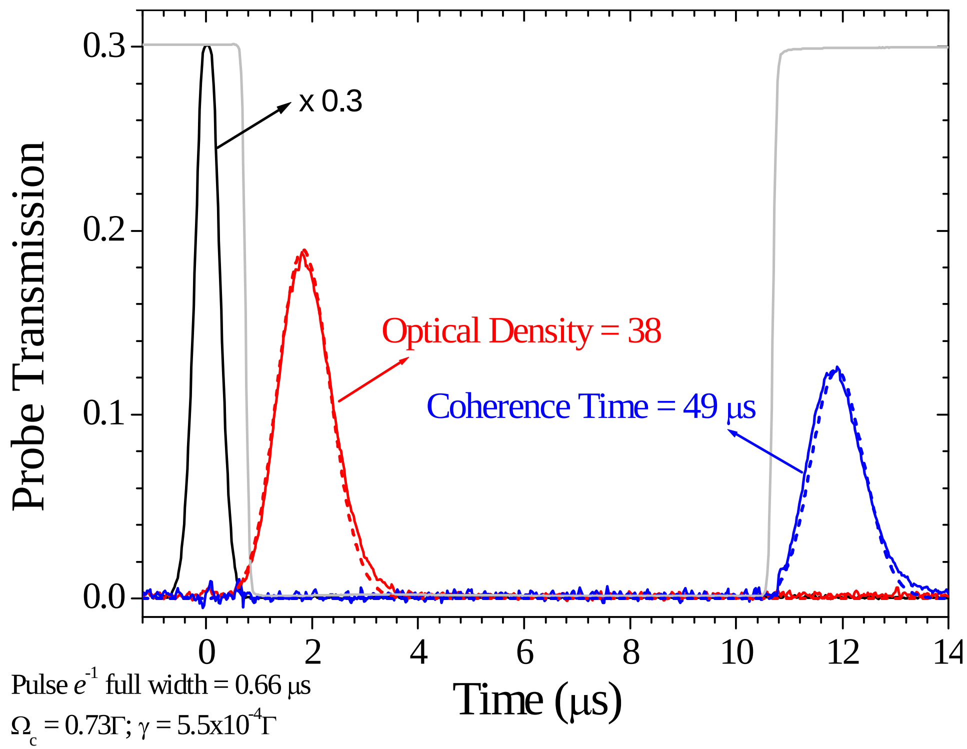

- The formation of SLPs requires a medium of large optical density (OD).
- SLPs do not require the standing wave or Bragg grating formed by the coupling fields, i.e., it is not necessary that $k^+ = k^-$.

# Develop Cigar-Shaped Cold Atom Clouds

Y. W. Lin, H. C. Chou, P. P. Dwivedi, Y. C. Chen, & *IAY*, **Opt. Express** 16, 3753 (2008).

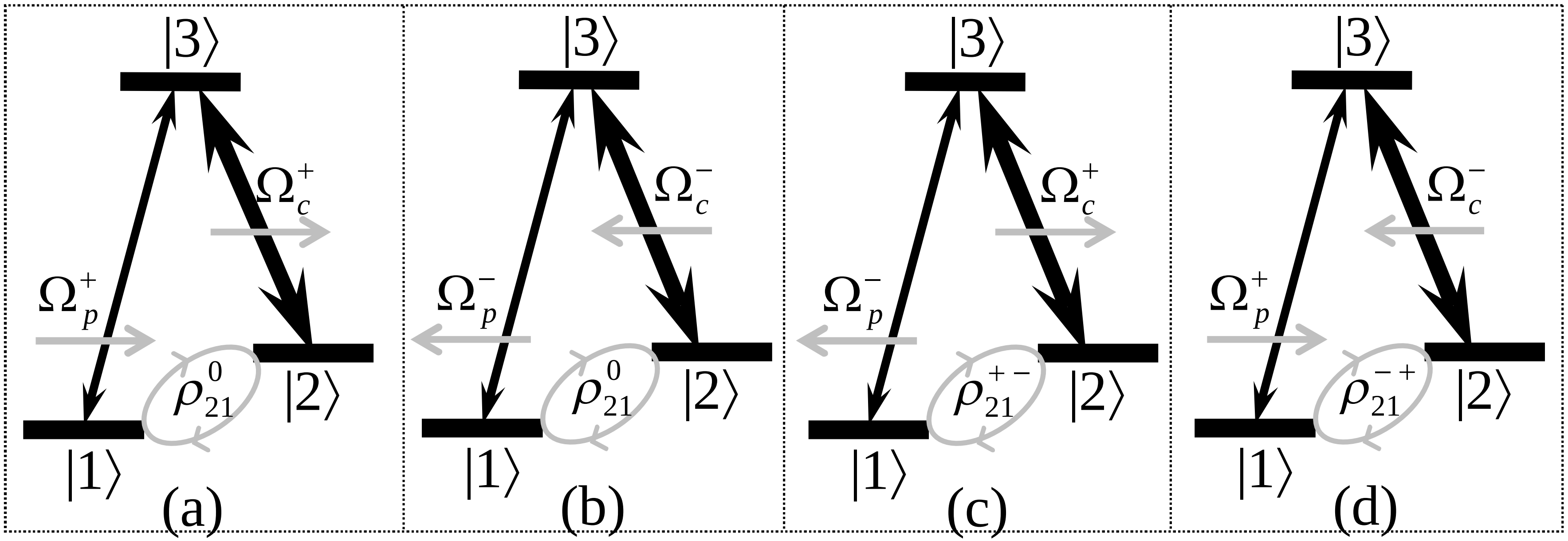


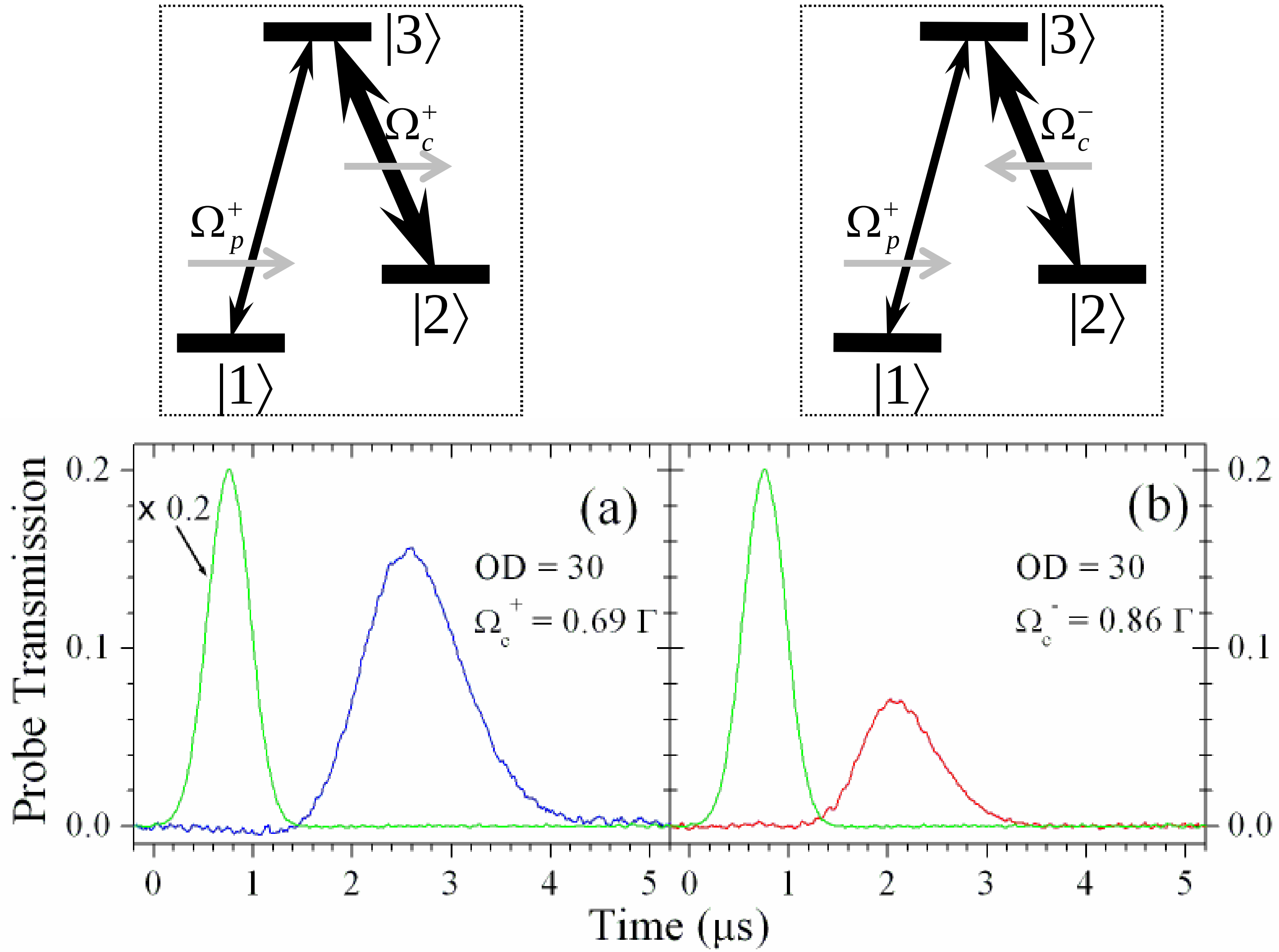

- The formation of SLPs requires a medium of large optical density (OD).
- The slow light data show OD = 38 which is enough large that a Gaussian pulse can be entirely stored in the atom cloud.
- The light storage data shows the coherence time is 49 μs.

# Raman Excitations in SLPs




- Figures (a) and (b) show the Raman excitations driven by co-propagating coupling and probe fields. Figures (c) and (d) show the Raman excitations driven by counter-propagating coupling and probe fields.
- For hot media, only (a) and (b) need to be considered; (c) and (d) are negligible because the EIT resonance condition can not be satisfied due to the Doppler shift.
- For cold media such as cold atoms, Bose condensates, and color-center crystals, (c) and (d) have to be considered.

# Co- and Counter-Propagating Slow Light Pulses




- Data in Fig. (a) can be obtained in both cold media and hot samples.
- Data in Fig. (b) can only be obtained in cold media, but not in hot samples.

# Equations for Cold Atomic Media

$$\frac{\partial \rho_{21}}{\partial t} = \frac{i}{2}(\Omega_c^+)^* \rho_{31}^+ + \frac{i}{2}(\Omega_c^-)^* \rho_{31}^- - \gamma \rho_{21},$$

$$\frac{\partial \rho_{31}^+}{\partial t} = \frac{i}{2}\Omega_p^+ + \frac{i}{2}\Omega_c^+ \rho_{21} - \frac{\Gamma}{2}\rho_{31}^+,$$

$$\frac{\partial \rho_{31}^-}{\partial t} = \frac{i}{2}\Omega_p^- + \frac{i}{2}\Omega_c^- \rho_{21} - \frac{\Gamma}{2}\rho_{31}^-,$$

$$\frac{1}{c}\frac{\partial \Omega_p^+}{\partial t} + \frac{\partial \Omega_p^+}{\partial z} = i\frac{\alpha\Gamma}{2L}\rho_{31}^+,$$

$$\frac{1}{c}\frac{\partial \Omega_p^-}{\partial t} - \frac{\partial \Omega_p^-}{\partial z} = i\frac{\alpha\Gamma}{2L}\rho_{31}^-.$$

$$\frac{\partial \rho_{31}^+}{\partial t} = \frac{i}{2}\Omega_p^+ + \frac{i}{2}(\Omega_c^+ \rho_{21}^0 + \Omega_c^- \rho_{21}^{-+}) - \frac{\Gamma}{2}\rho_{31}^+,$$

$$\frac{\partial \rho_{31}^-}{\partial t} = \frac{i}{2}\Omega_p^- + \frac{i}{2}(\Omega_c^- \rho_{21}^0 + \Omega_c^+ \rho_{21}^{+-}) - \frac{\Gamma}{2}\rho_{31}^-,$$

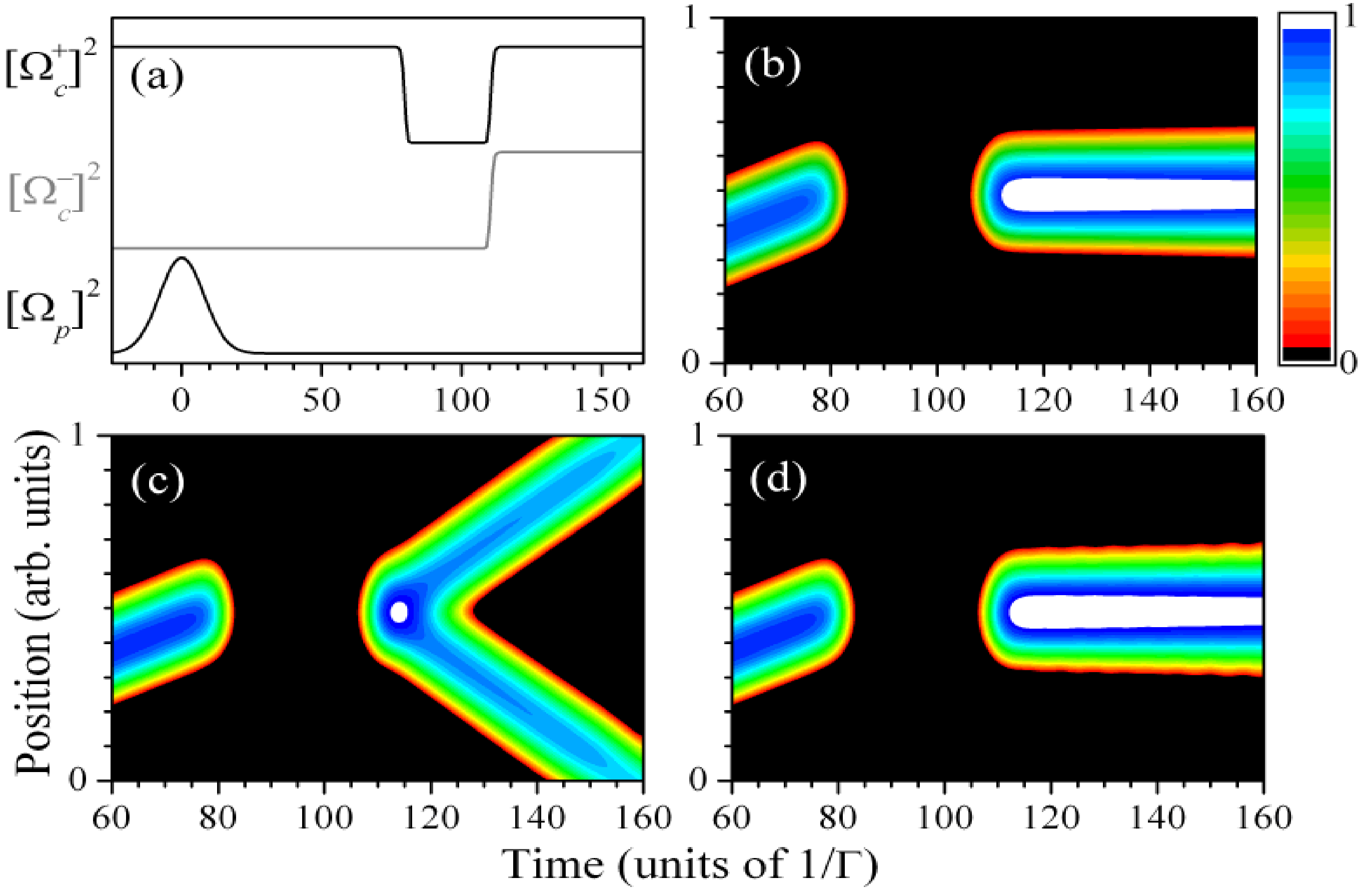
$$\frac{\partial \rho_{21}^{+-}}{\partial t} = \frac{i}{2}(\Omega_c^+)^* \rho_{31}^- - \gamma_2 \rho_{21}^{+-},$$

$$\frac{\partial \rho_{21}^{-+}}{\partial t} = \frac{i}{2}(\Omega_c^-)^* \rho_{31}^+ - \gamma_2 \rho_{21}^{-+},$$

$$\frac{\partial \rho_{21}^{0}}{\partial t} = \frac{i}{2}[(\Omega_c^+)^* \rho_{31}^+ + (\Omega_c^-)^* \rho_{31}^-] - \gamma_1 \rho_{21}^0,$$

- In order to take the counter-propagating Raman excitations into account, we modify the optical Bloch equations.
- $\rho_{21} \rightarrow \rho_{21}^0 + \rho_{21}^{+-}\exp(-2ikz) + \rho_{21}^{-+}\exp(2ikz).$
- $\rho_{21}^0$ is resulted from the co-propagating Raman excitations.
- $\rho_{21}^{+-}$ and $\rho_{21}^{-+}$ are resulted from the counter-propagating Raman excitations.
- For hot media, $\rho_{21}^{+-} = \rho_{21}^{-+} = 0.$

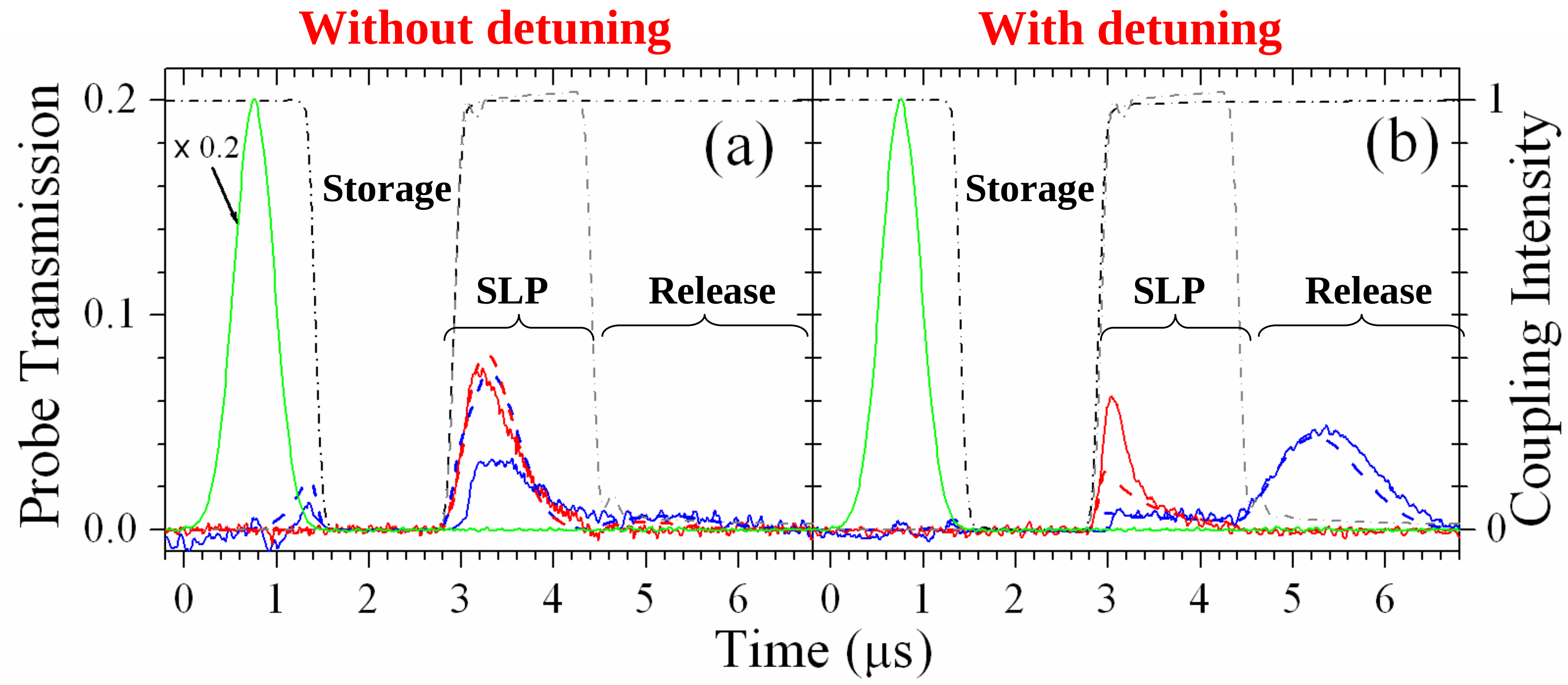
# Predictions from Cold-Atom Equations




- In (b), the counter-propagating Raman excitations are set to zero.
- In (c), the counter-propagating Raman excitations are considered. No SLP is formed. Instead, the probe pulse splits up into two counter-propagating pulses.
- In (d), a detuning is applied in the backward coupling field to destroy the counter-propagating Raman excitations.

# Realization of SLPs in Cold Atoms

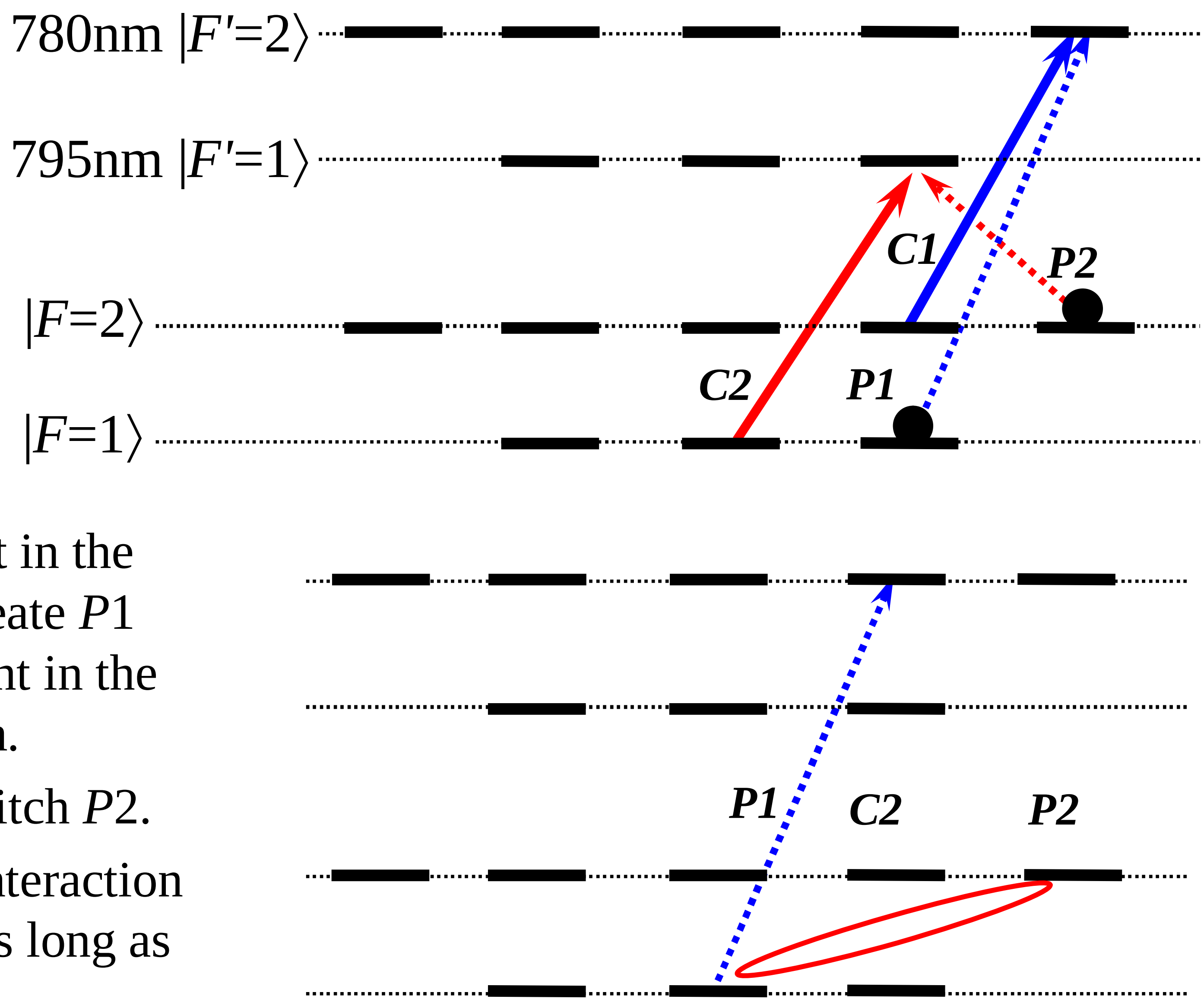
Y. W. Lin, W. T. Liao, T. Peters, H. C. Chou, J. S. Wang, H. W. Cho, P. C. Kuan, & *IAY*,
**PRL** 102, 213601 (2009).




- The pulse visible for $t > 4.5$ μs represents the remaining energy of the initial probe pulse after a SLP duration of 1.5 μs.
- While the SLP was established, the probe signals leaked out of the medium in the forward and backward directions.
- We demonstrated a SLP in cold atoms. ⇒ An optical cavity of $Q \sim 10^9$.

# Outlook — Stored Light Switched by Stationary Light

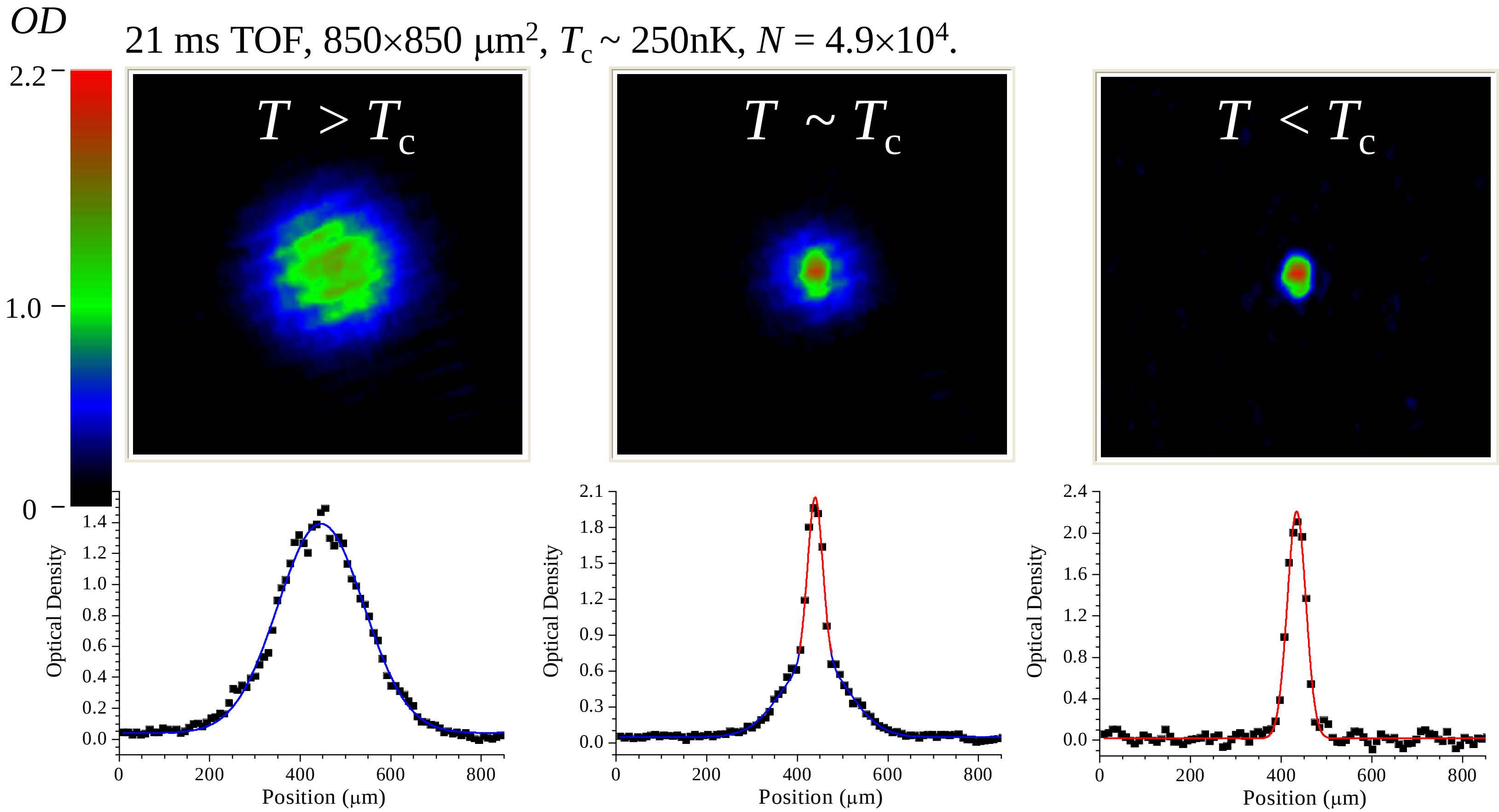
**Two EIT Systems**




- Store $P2$ light in the atoms and create $P1$ stationary light in the same medium.
- Use $P1$ to switch $P2$.
- Ideally, the interaction time can be as long as possible.

# Outlook — BEC for Single-Photon Experiments

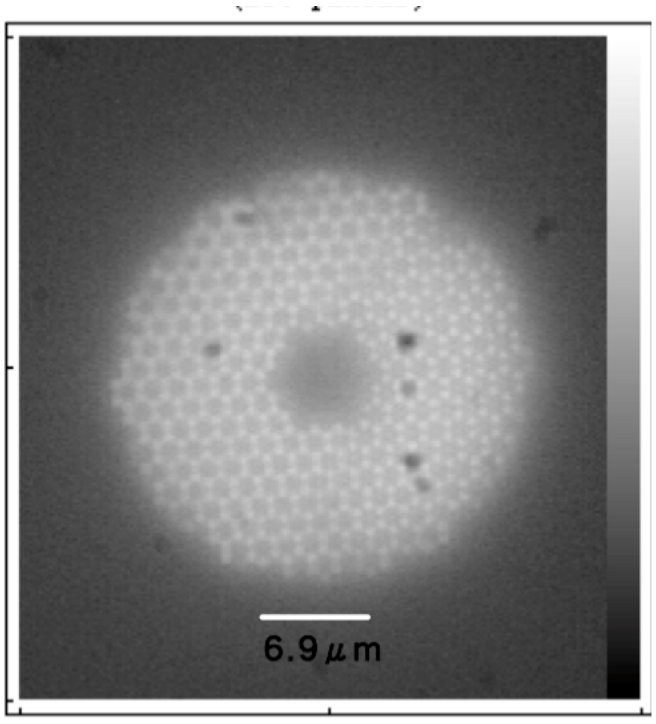
H. W. Cho, Y. C. He, T. Peters, Y. H. Chen, H. C. Chen, S. C. Lin, Y. C. Lee, & *IAY*,
**Opt. Express** 15, 12114 (2007).




- Tightly focus single-photon pulses to maximize the intensity. The smallest size is the order of λ and, hence, the Gaussian beam diverges in a distance of λ.
- The BEC density is well above $10^{13}$ atoms/cm³ (≈ 5 atoms per $\lambda^3$).

# Outlook — Cold Atoms in a Photonic Crystal Fiber

- Laser beams propagate a long distance through optical fibers and still maintain a rather small beam waist.
- Cold atoms will be trapped in a hollow-core photonic crystal fiber by an optical dipole beam.
- If we can trap 100,000 atoms in the PCF, the optical density can be on the order of magnitude of a few hundreds.
- Manipulation of quantum information becomes practical.
- Quantum nondemolition measurement, quantum phase gates, and entangled photon pairs.



# Acknowledgements

**NSC** 98-2628-M-007-001; **NTHU** Boost Energy Project

**Stationary Light Pulses:** Yen-Wei Lin,[1] Hung-Chih Chou,[2] Thorsten Peters,[3] Wen-Te Liao,[4] Hung-Wen Cho,[5] Jian-Siung Wang,[6] Pei-Chen Kuan

**http://atomcool.phys.nthu.edu.tw/**

# ***Thank you for your attention.***

**Postdoc position available; 歡迎碩、博士生加入研究小組。**

**contact: yu@phys.nthu.edu.tw**