Spinor Slow Light
and
Two-Color Qubits

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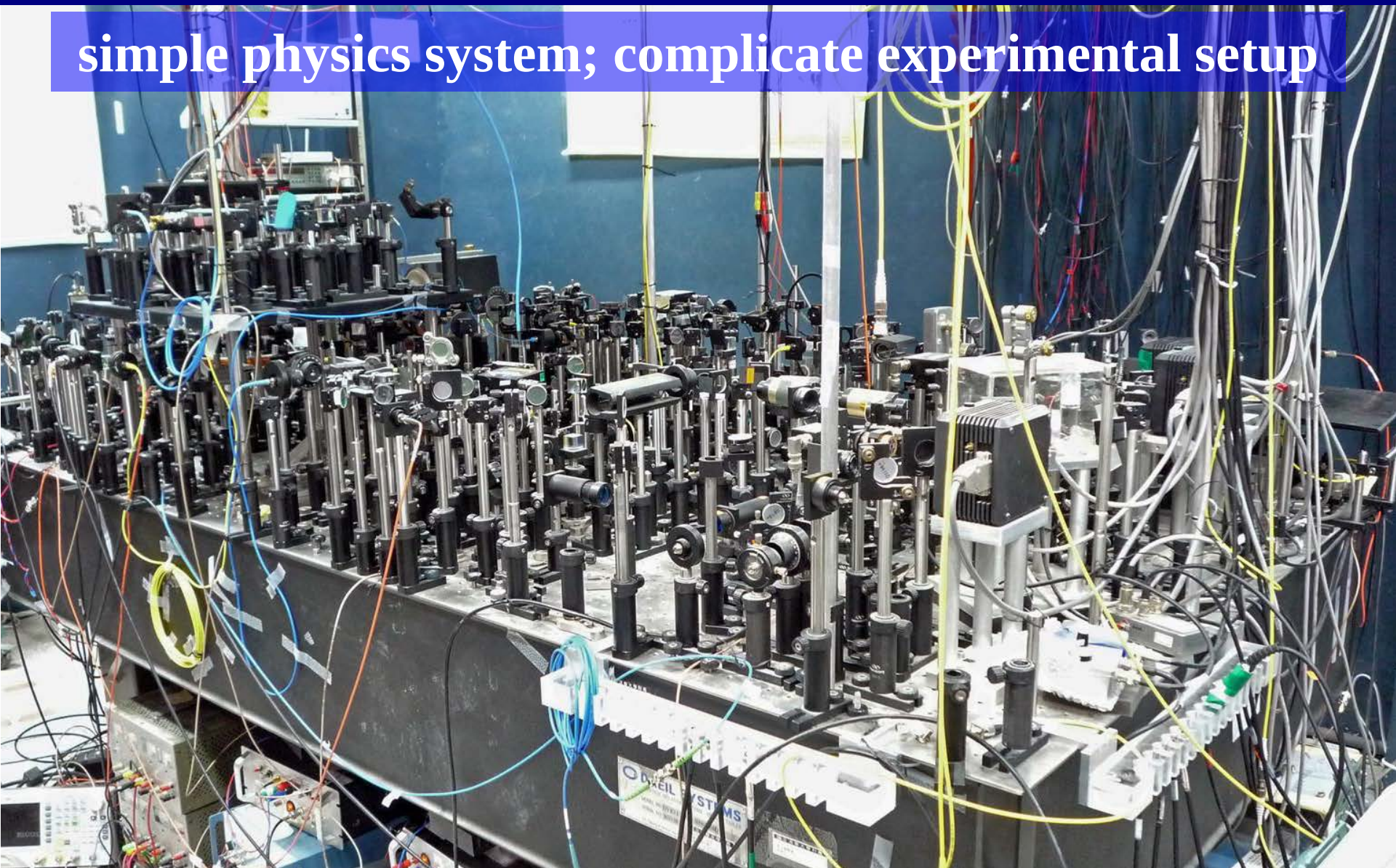
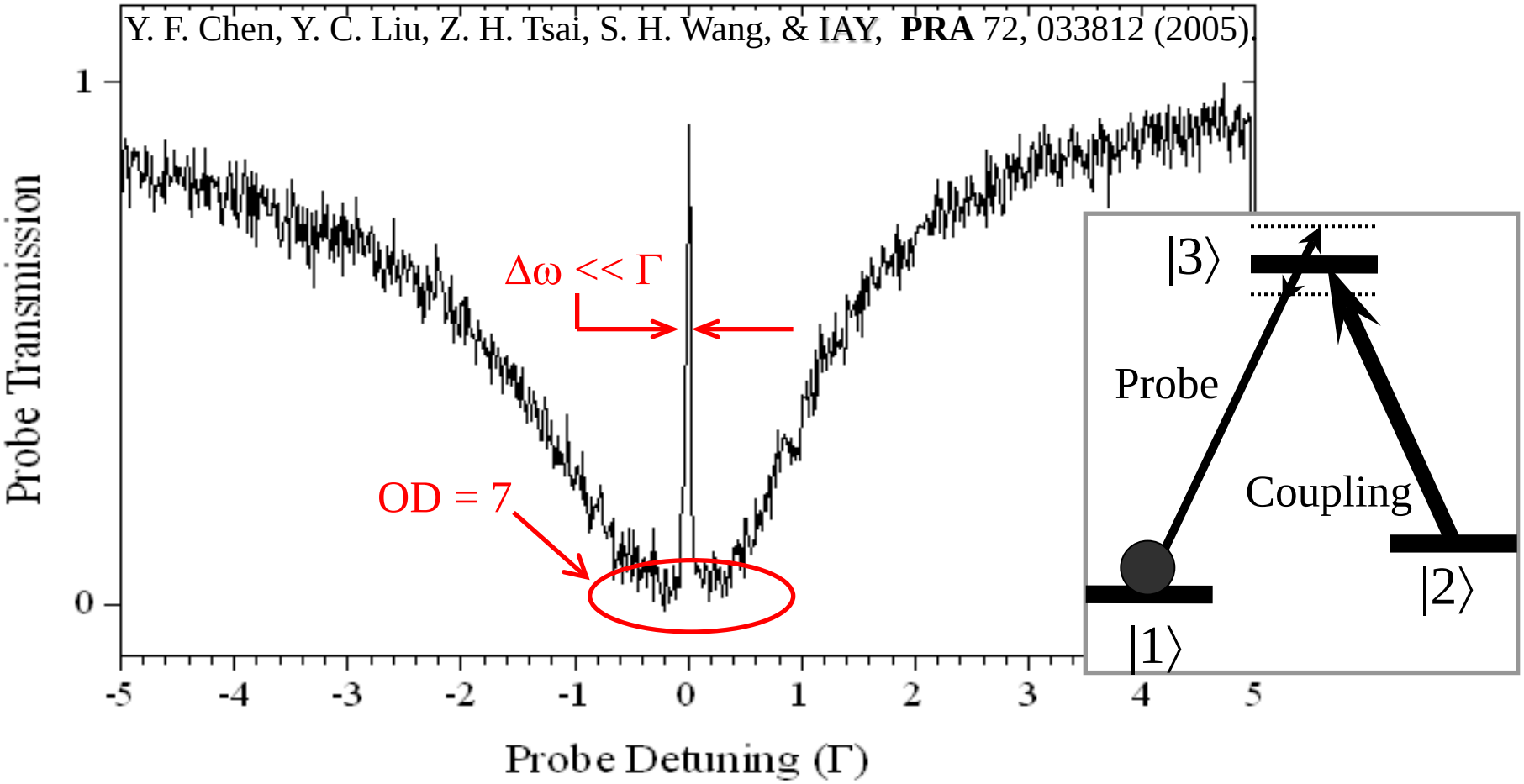
NTHU Optical Jungle

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

simple physics system; complicate experimental setup

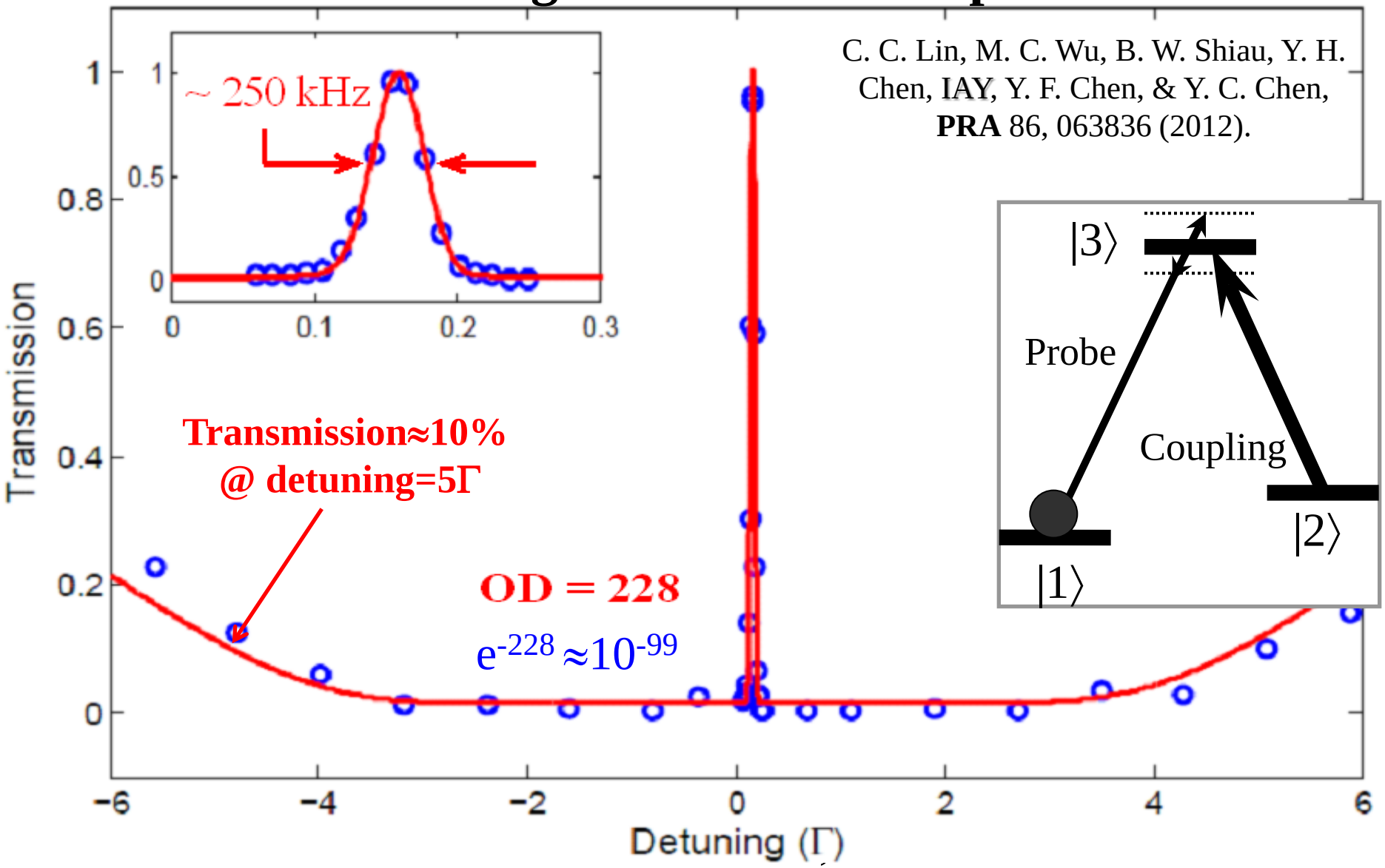


Narrow and High-Contrast EIT Spectrum



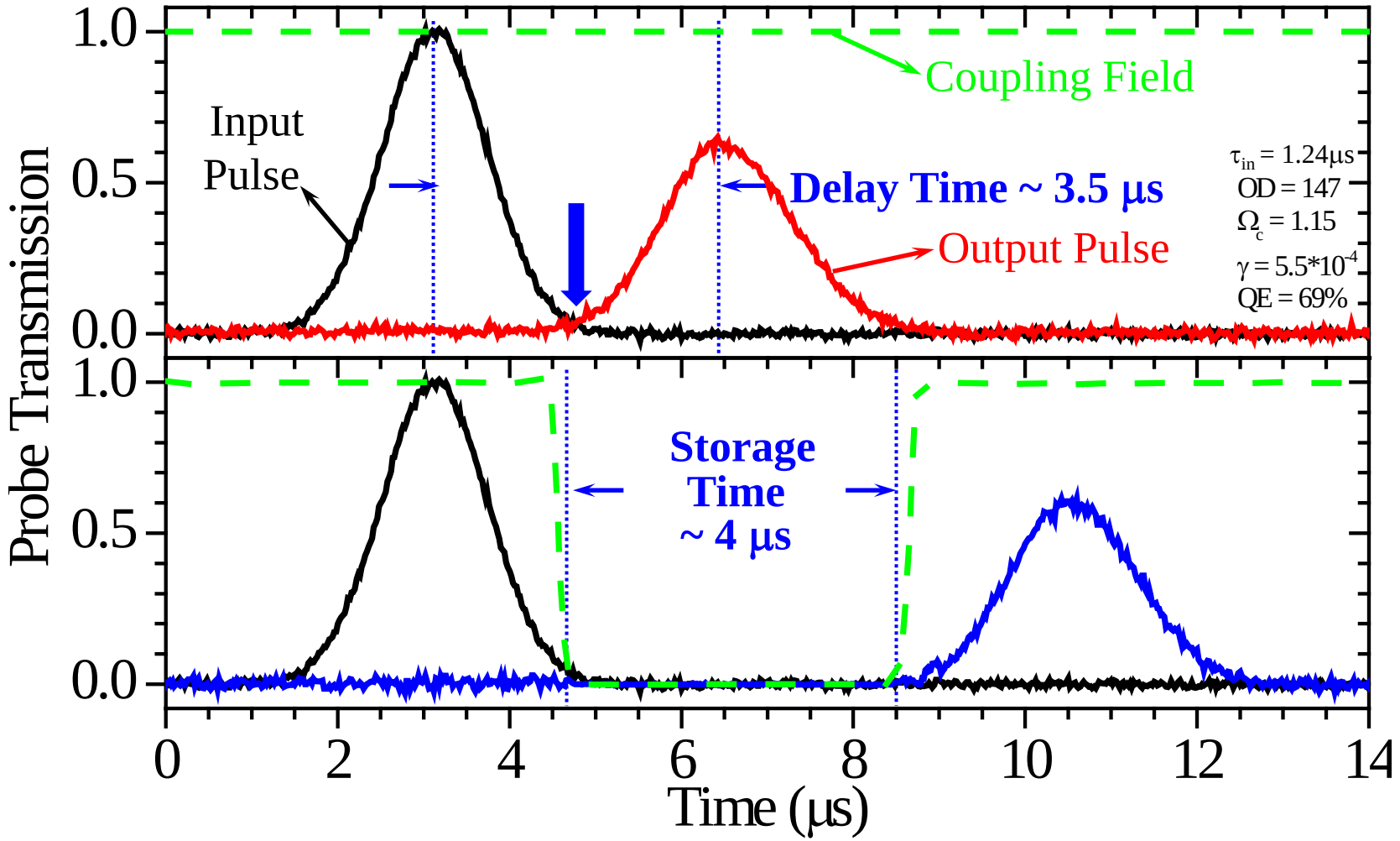
- Near the resonance, OD = 7 and probe transmission is e^{-7} (less than 0.1%).
- Transmission is nearly 100% at the resonance and the transparency window is much narrower than the natural linewidth, Γ.
- Narrow & high-contrast absorption profile => **large dispersion** => **slow group velocity**.

Narrow and High-Contrast EIT Spectrum



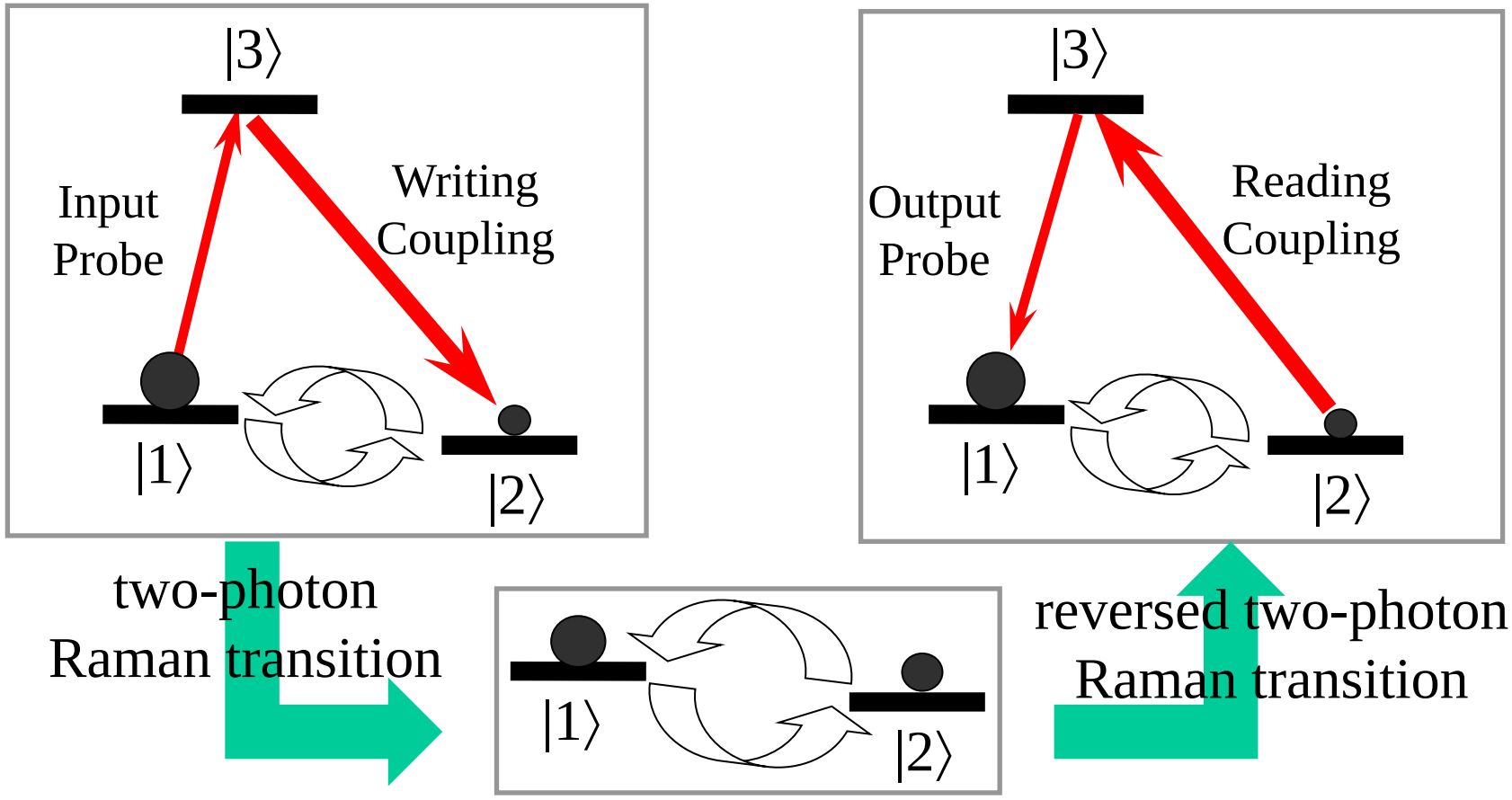
- Narrow & high-contrast absorption profile => **large dispersion** => **slow group velocity**.

Slow Light and Storage of Light



- In the constant presence of the coupling, speed of the light pulse $\leq c/10^5$.
- The 1 km-long probe pulse is compressed to 1 cm inside the atoms.
- The gap of ~ 4 μs in the probe signal demonstrates the light storage.

Coherent Storage for Photons



atomic wave function: **ground-state**

(Raman) coherence or spin excitation

The EIT storage is a coherent process and provides a method for exchange of wave functions between photons and atoms.

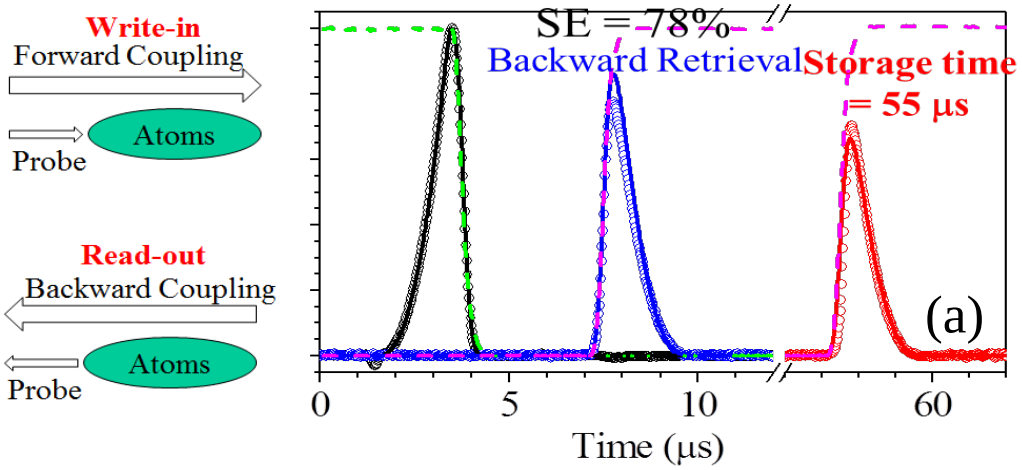
High Storage Efficiency and Large Delay-Bandwidth Product

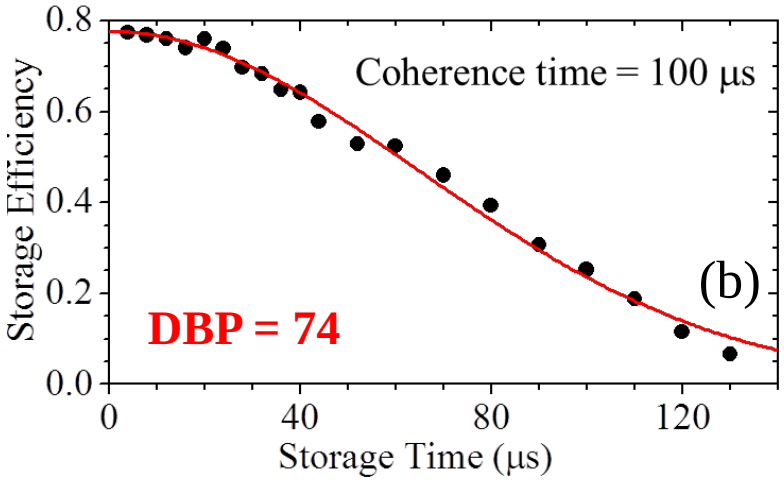
Y. H. Chen, M. J. Lee, I. C. Wang, S. Du, Y. F. Chen, Y. C. Chen, & IAY,

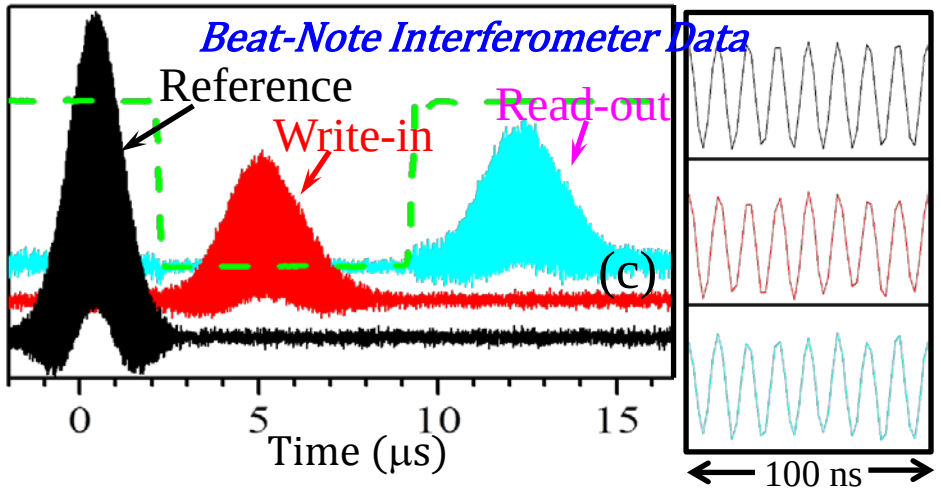
PRL 110, 083601 (2013).

$$\text{SE} \equiv \frac{E_{\text{out}}}{E_{\text{in}}} \qquad \text{DBP} \equiv \frac{t_{\text{storage}}}{t_{\text{pulse}}}$$

$$\text{Fidelity} \equiv \frac{|\langle\psi_{\text{out}}|\psi_{\text{in}}\rangle|^2}{\langle\psi_{\text{in}}|\psi_{\text{in}}\rangle\langle\psi_{\text{out}}|\psi_{\text{out}}\rangle}$$





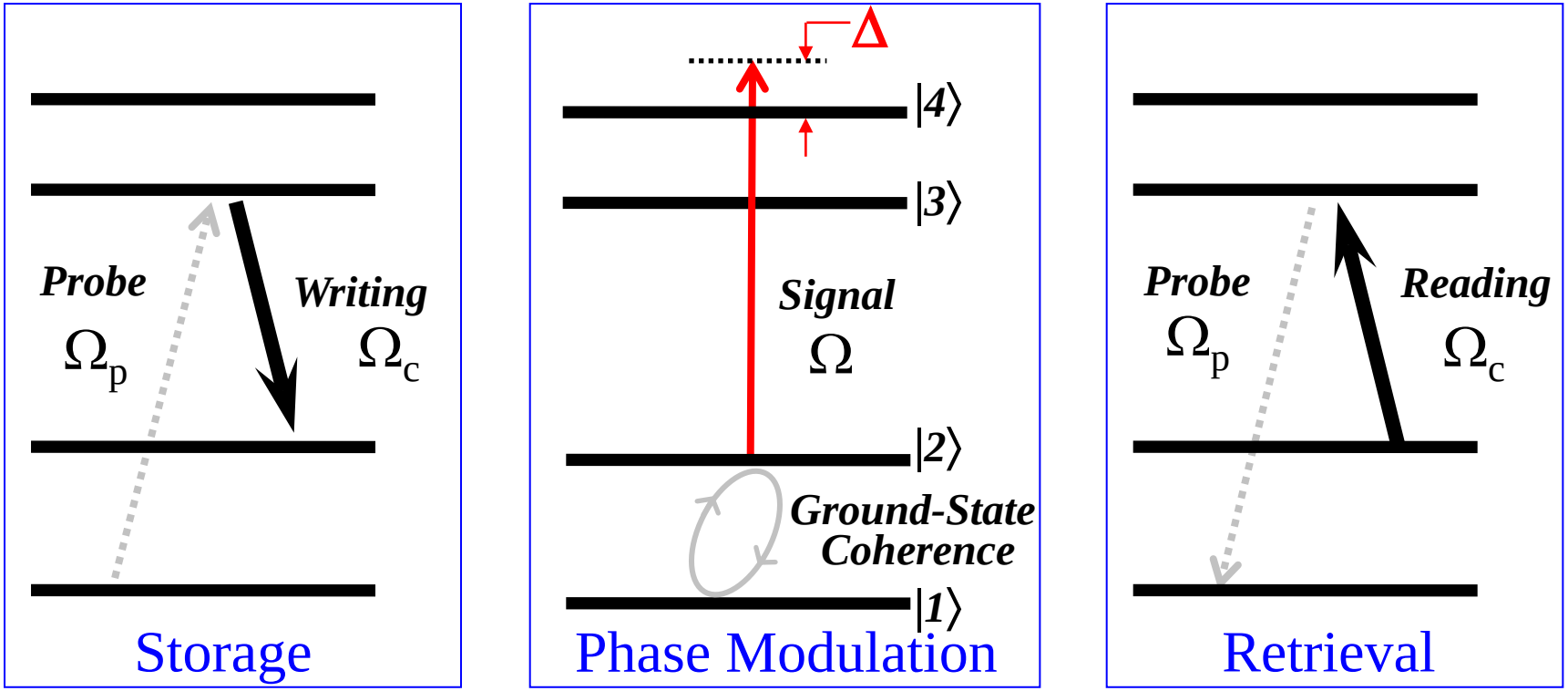


- Optimal pulse shape & backward retrieval to enhance SE.
- We report a EIT memory with storage efficiency of 78%, delay-bandwidth product of 74 at SE = 50%, and fidelity ≥ 0.9.

Low-Light-Level Nonlinear Optics

Cross-Phase Modulation (XPM) based on Stored Light

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



- The stored ground-state coherence is equivalent to the probe pulse.
- Single-photon XPM or AOS: quantum phase gates, entangled photon pairs, quantum nondemolition measurements.
- XPM: a phase shift of 44° is obtained at 18 photons per atomic absorption cross section. How to further improve?

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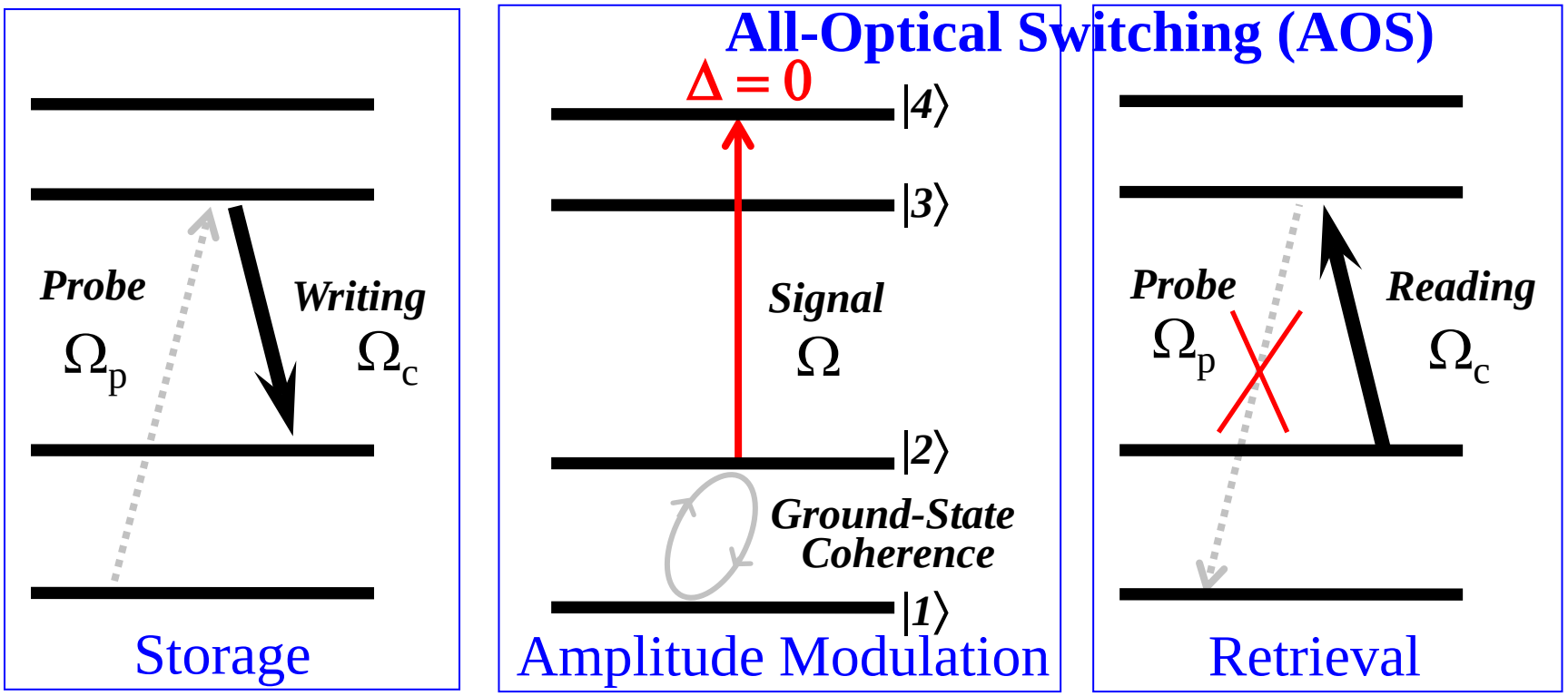

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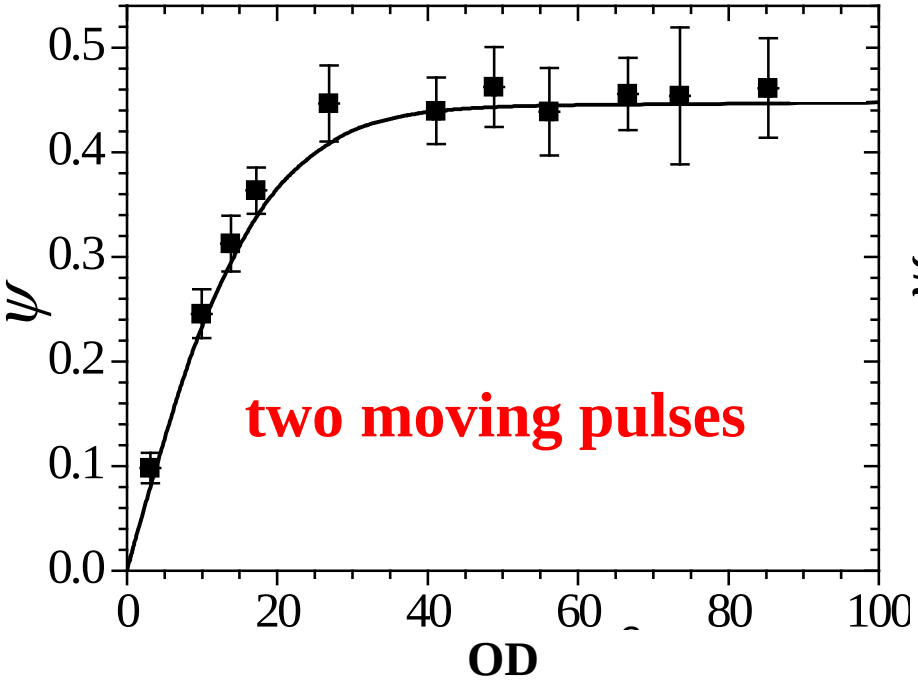
- XPM: a phase shift of 44° is obtained at 18 photons per atomic absorption cross section. How to further improve?

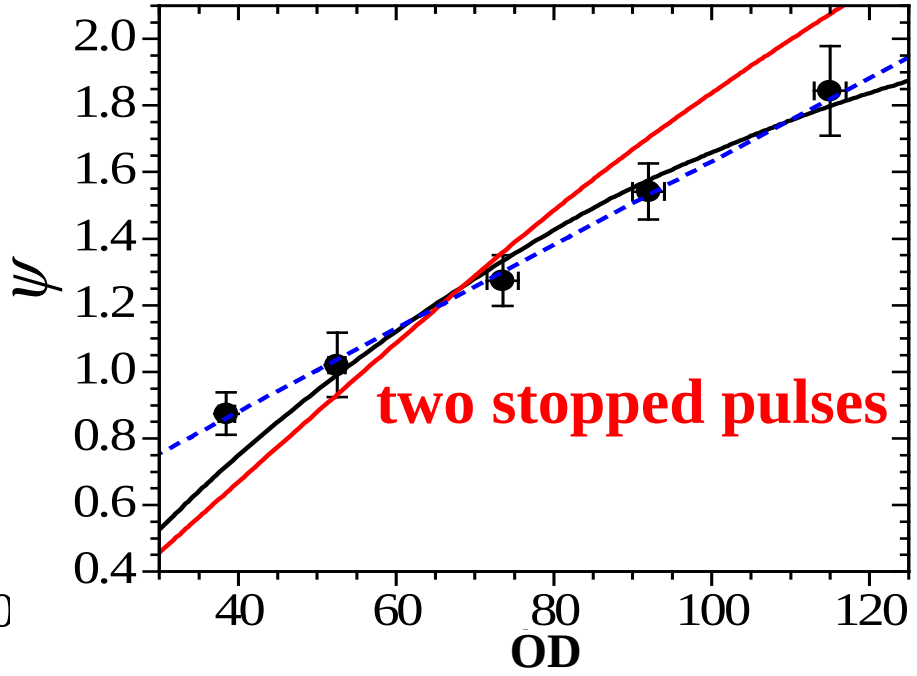
All-Optical Switching with Stopped Light Pulses

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).

Y. H. Chen, M.J . Lee, W. Hung, Y. C. Chen, Y. F. Chen, & IAY,
PRL 108, 173603 (2012).

Switching Ratio = $\exp[-\psi(N/A)\sigma]$





- The interaction time can be, in principle, as long as possible.
- 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.

Nature Physics, April 2012, p. 252.

research highlights

Liquids in no man's land

Nature Mater. http://doi.org/hrm (2012)

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When it comes to its physical properties,

enabling the authors to identify a distinct transition between low- and high-density liquid states, providing the strongest suggestion so far that such a transition should indeed be possible in pure water. *EG*

Frozen light switch

Phys. Rev. Lett. (in the press); preprint at http://arxiv.org/abs/1111.2110 (2011)

Enhancing the efficiency of optical switching or other nonlinear optical processes usually requires high-intensity light. However, it is also possible to maximize efficiency with very-low-intensity light if the interaction time is long. Stopping light pulses and making them interact in a medium is a way to get more for less.

Yi-Hsin Chen and co-workers made two light pulses motionless by slowing

speeds and lower power consumption than the prevalent electronic equivalent. Kengo Nozaki and colleagues have now demonstrated writing, storing and erasing of data in a photonic-crystal-nanocavity memory that uses 300 times less power than previous devices.

A key characteristic of the optical element is the ability to stably switch between two states: '0' and '1'. Such optical switches have been demonstrated using [illegible] lasers, but the devices were bulky and didn't take full advantage of the potential power savings offered by optics.

Nozaki *et al.* use a photonic-crystal cavity in which, above a threshold input power, the light transmittance can take one of two stable values. Decreasing the volume and increasing the quality factor of the cavity reduces this threshold, enabling more efficient operation.

Stopping light pulses and making them interact in a medium is a way to get more for less.

Frozen "light switch" **"Frozen light" switch√**

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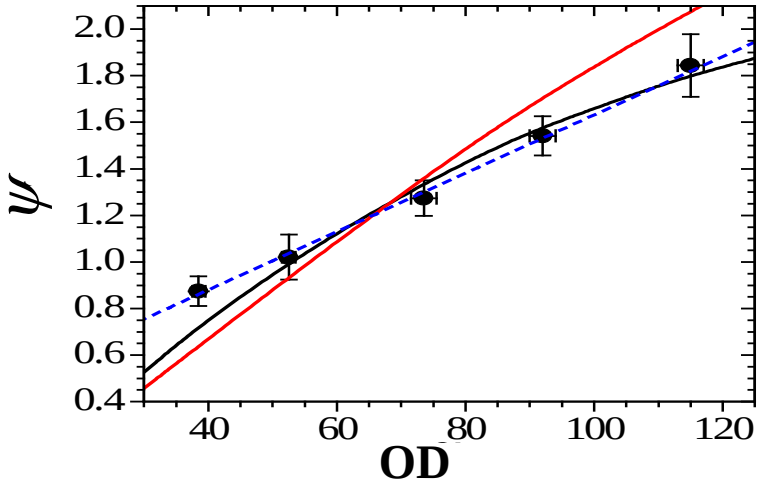
Summary of EIT, Slow Light and Stored Light

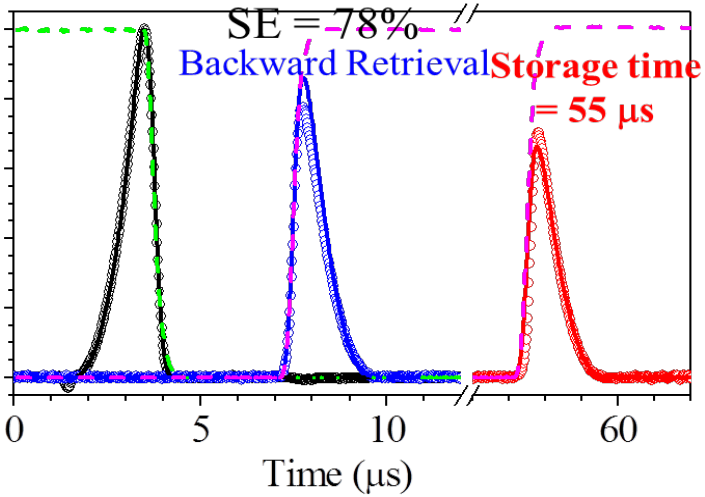
- Acknowledgments to collaborators:

  Prof. Yong-Fan Chen (PHYS, NCKU)

  Dr. Ying-Cheng Chen (IAMS, AS)



- The EIT/slow light effect enhances the light-matter interaction and achieves significant nonlinear optical efficiency even at single-photon level.



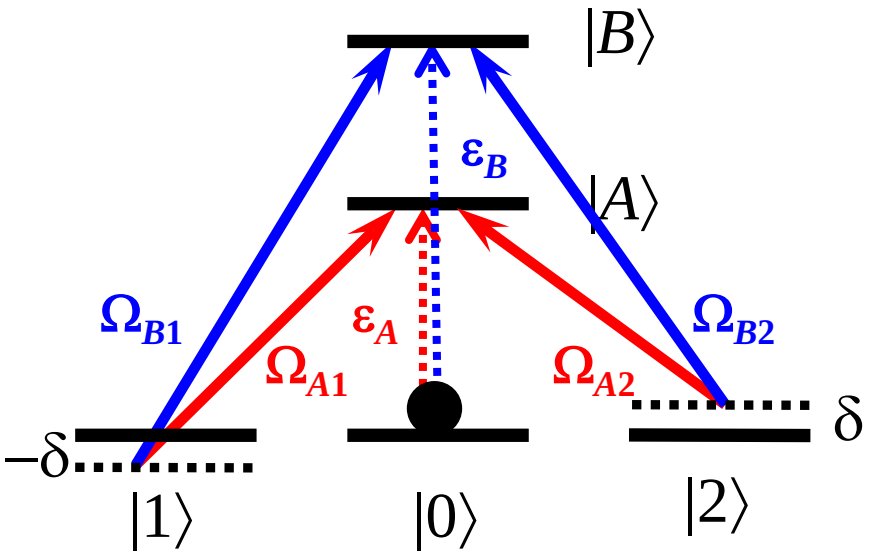
- EIT-based storage of slow light transfers quantum states between photons and atoms, making quantum memory feasible.

- However, previous experiments all dealt with **single-component slow light**.

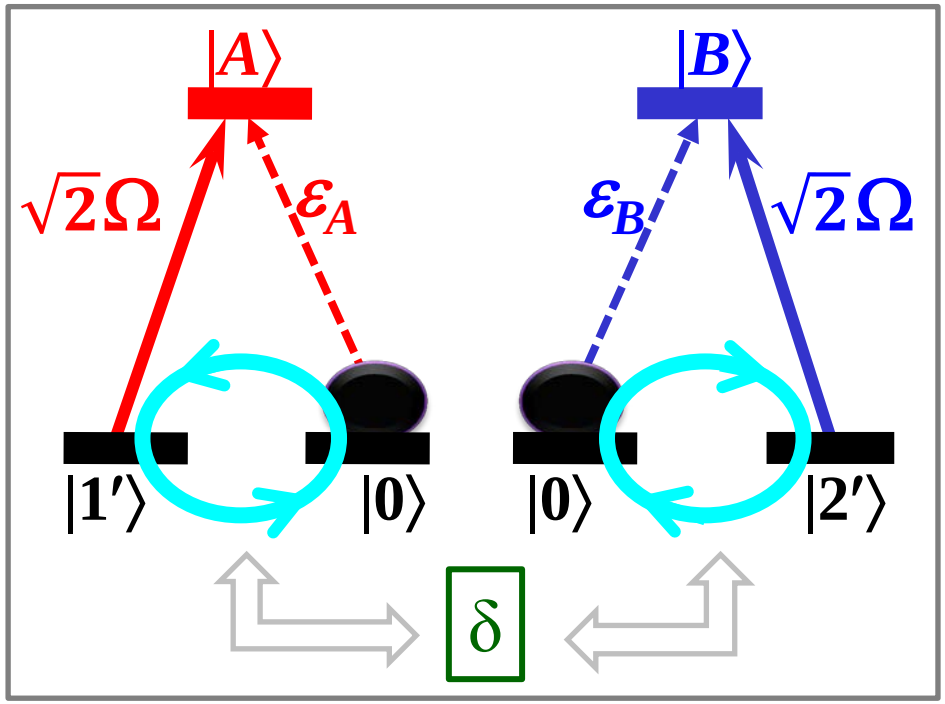
Double Tripod System

Three atomic ground states coupled to two excited states by 4 coupling fields Ω_{A1}, Ω_{A2}, Ω_{B1} & Ω_{B2} and 2 probe fields ε_A & ε_B.

Spinor (Two-Component) Slow Light



DT ≡ Two Coupled EITs



$$\Omega_{A1} = \Omega_{A2} = \Omega_{B1} = \Omega_{B2} \equiv \Omega,$$

$$\begin{pmatrix} \varepsilon_{A,out} \\ \varepsilon_{B,out} \end{pmatrix} = e^{-(2\phi^2/\mathrm{OD})} \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} \varepsilon_{A,in} \\ \varepsilon_{B,in} \end{pmatrix}, \qquad \phi = \frac{\mathrm{OD}\,\Gamma}{2\Omega^2}\delta$$

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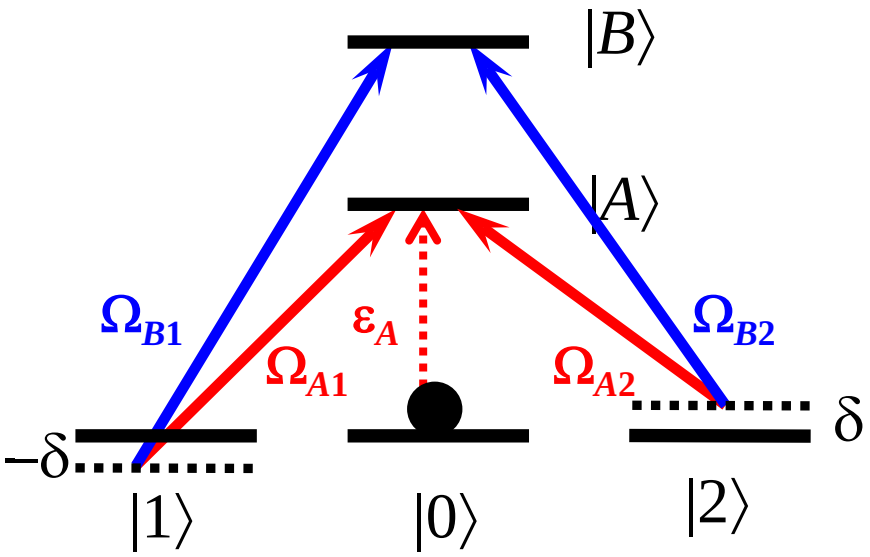

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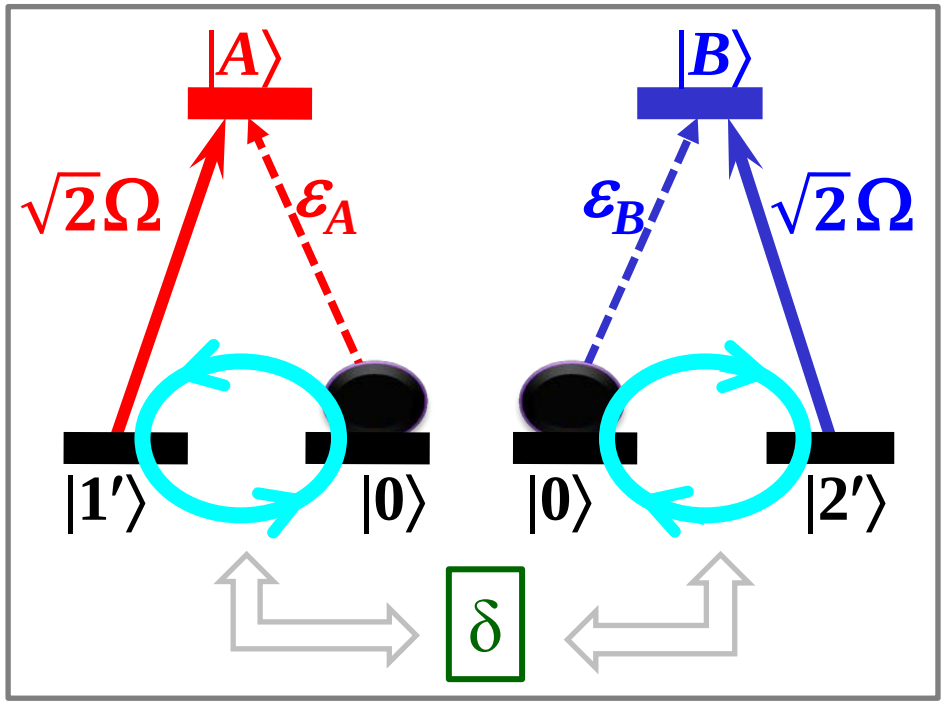

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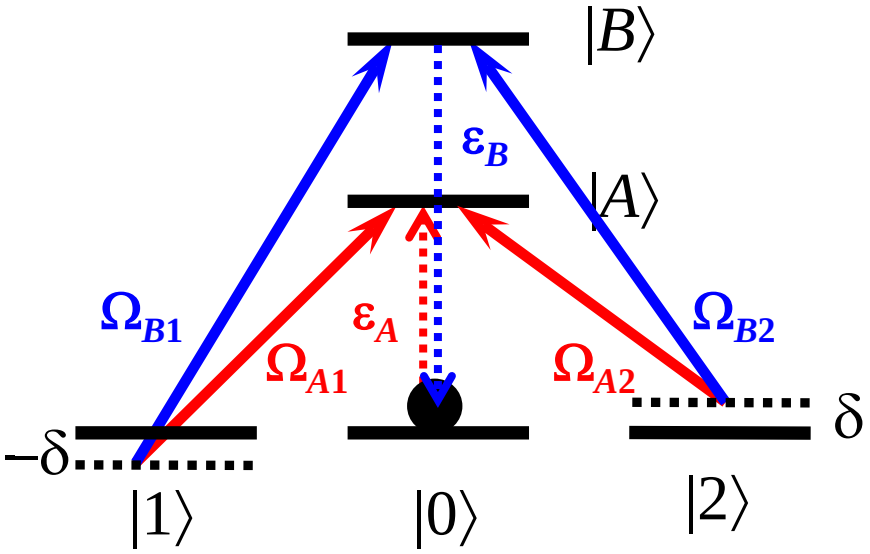

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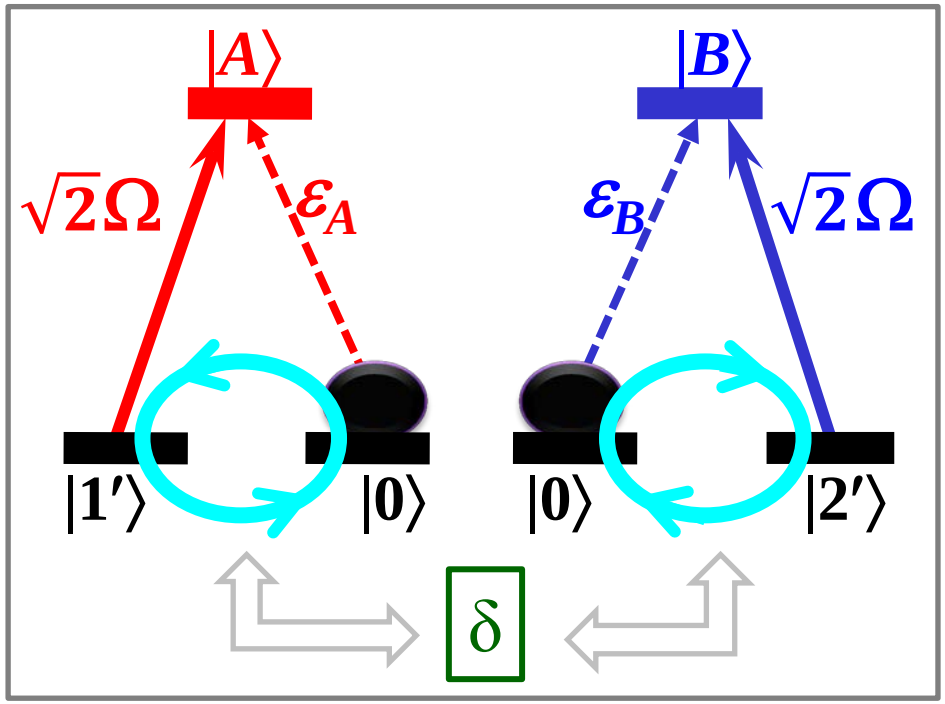

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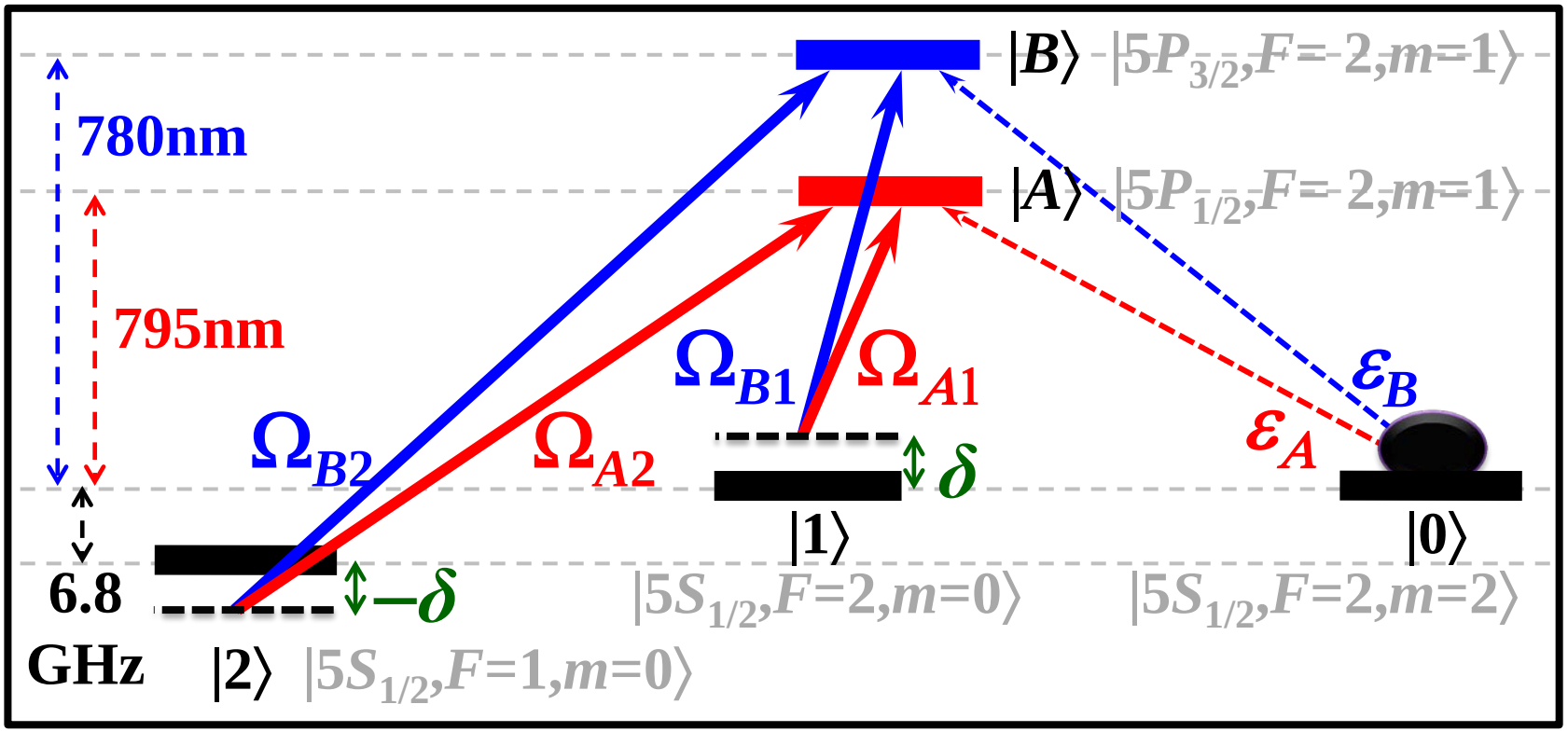
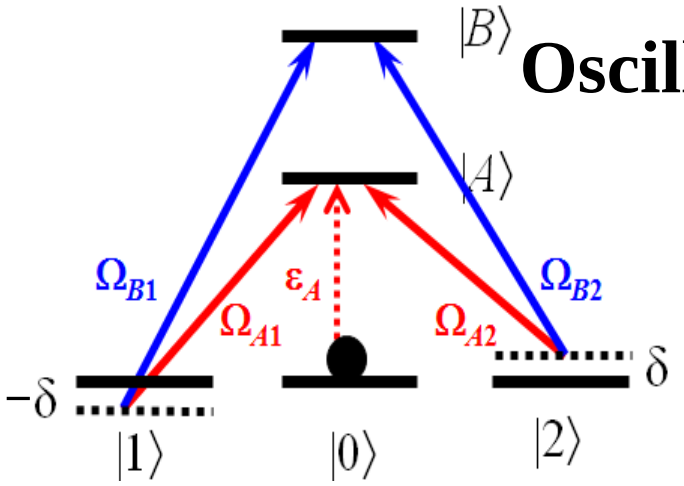
Transition Scheme



- Optically pump all population to a single Zeeman state ⇒ A simple 5-level DT system.
- λ of the probe field *A* and the coupling fields *A*1 & *A*2 is ~ 795 nm.
- λ of the probe field *B* and the coupling fields *B*1 & *B*2 is ~ 780 nm.

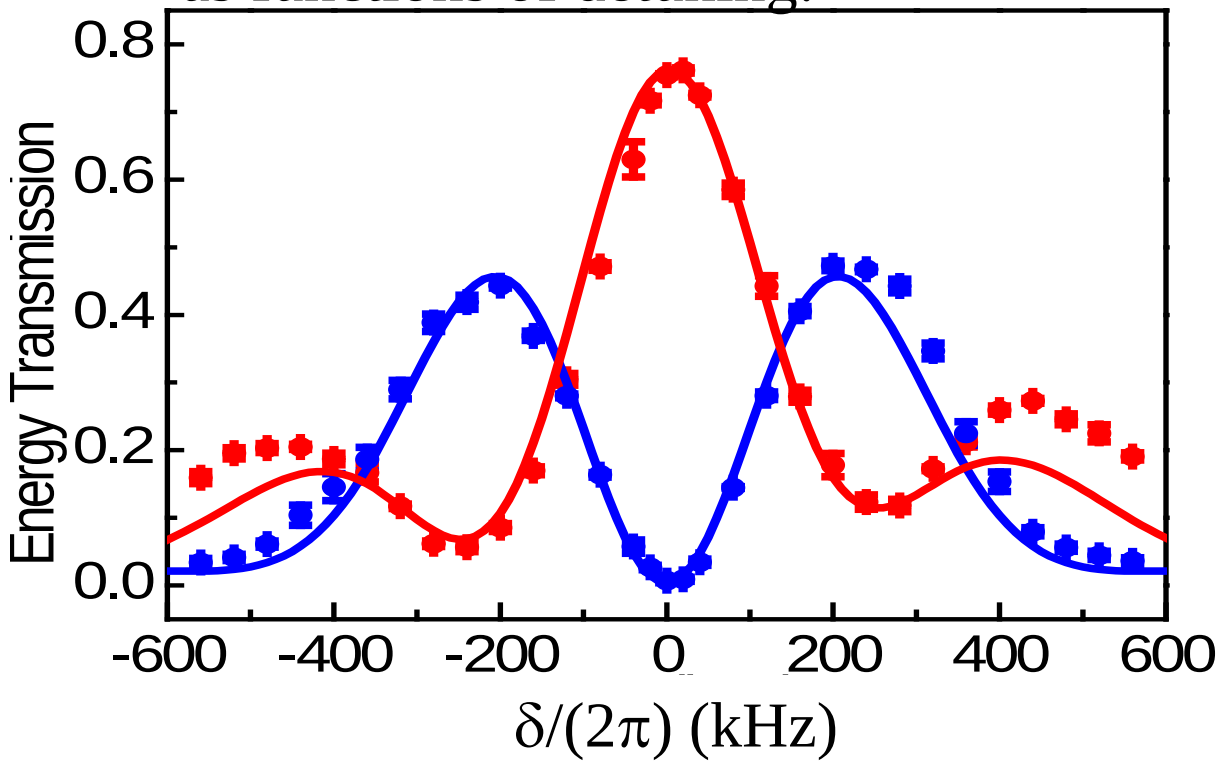
Oscillation between the Two Components



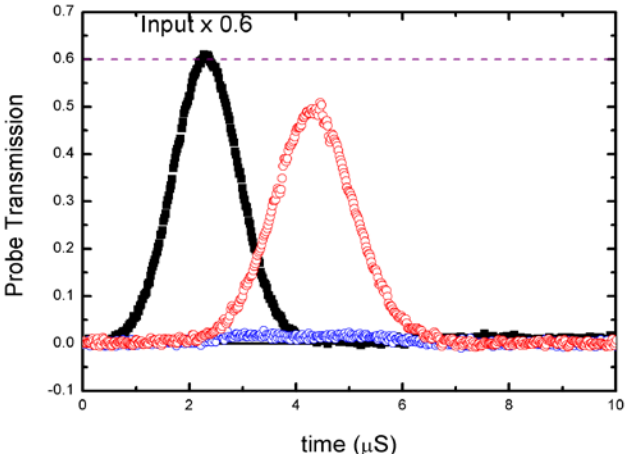
$$\begin{pmatrix} |\varepsilon_{A,out}|^2 \\ |\varepsilon_{B,out}|^2 \end{pmatrix} = e^{-(4\phi^2/\mathrm{OD})} \begin{pmatrix} \cos^2\phi \\ \sin^2\phi \end{pmatrix},$$

where $\phi = \dfrac{\mathrm{OD}\,\Gamma}{2\Omega^2}\delta.$

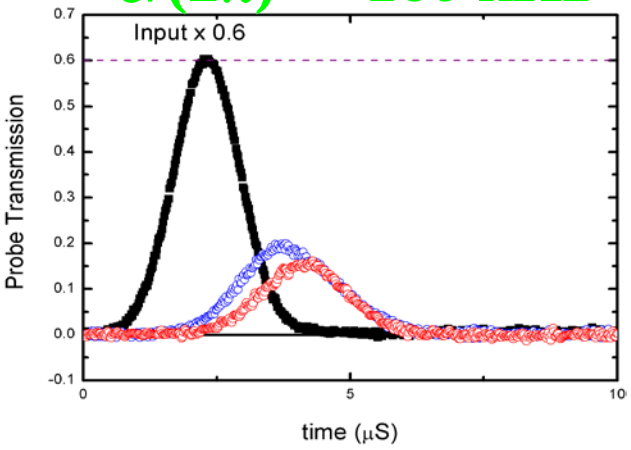
Output probe *A* (red) & probe *B* (blue) as functions of detuning:



δ = 0



δ/(2π) = -160 kHz



Stored Spinor Slow Light

$$\begin{pmatrix} \mathcal{E}_{A,out} \\ \mathcal{E}_{B,out} \end{pmatrix} = e^{-(2\phi^2/\mathrm{OD})} \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \text{ where } \phi = \frac{\mathrm{OD}\,\Gamma}{2\Omega^2}\delta.$$

OD $\Gamma/(2\Omega^2)$ is the delay time of slow light propagation, i.e. $\phi = \tau_d\delta$.

Can τ_d be replaced by τ_s (storage time)?

Stored Spinor Slow Light

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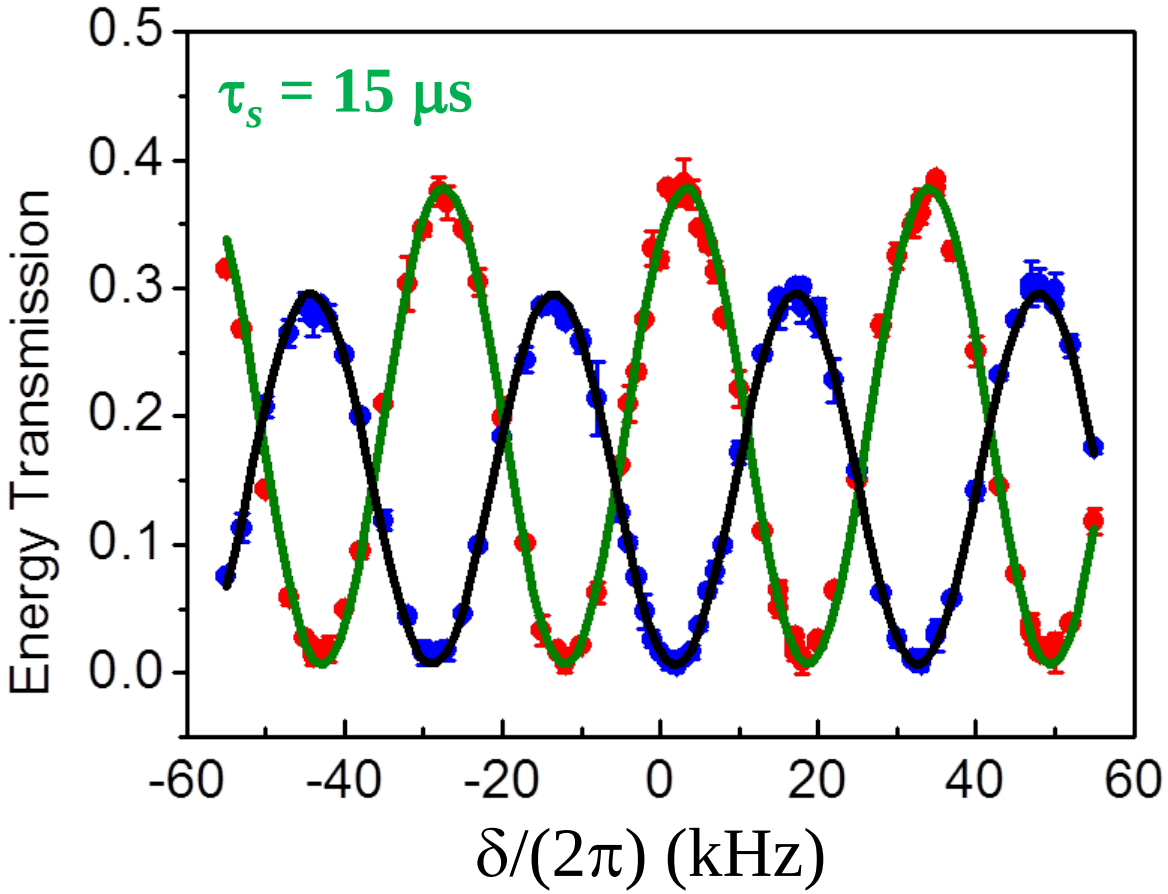
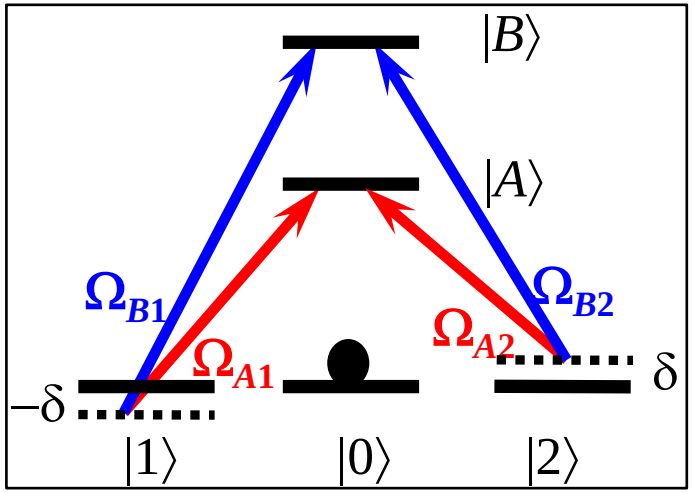


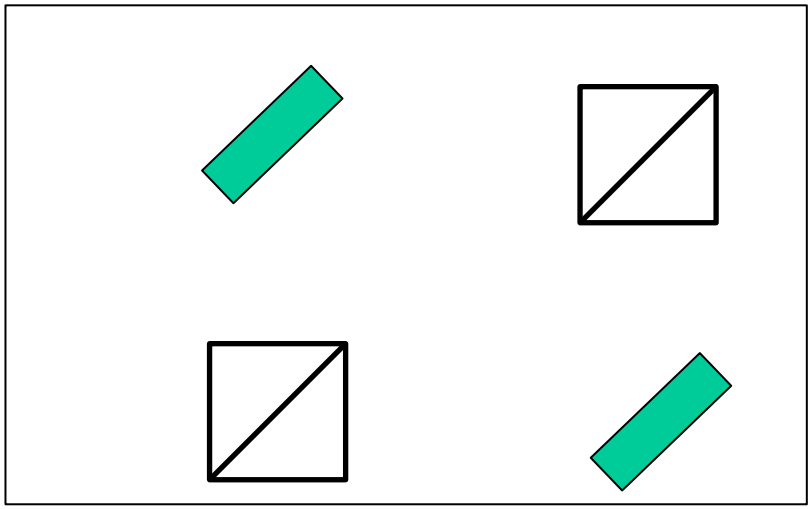
Large phase change & little decay

⇓

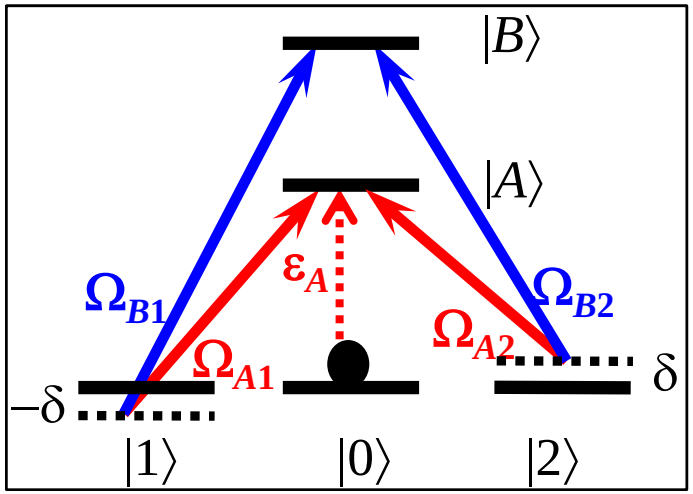
Phase-sensitive detector or interferometer

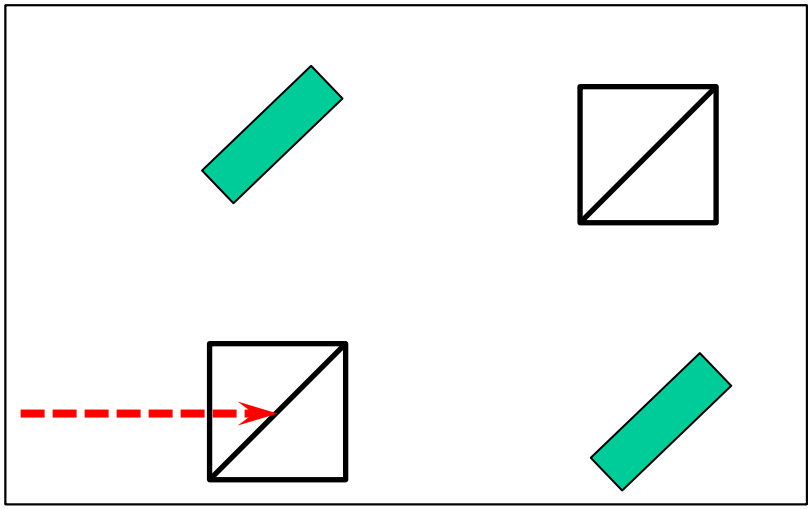
Interferometer based on Stored Spinor Slow Light



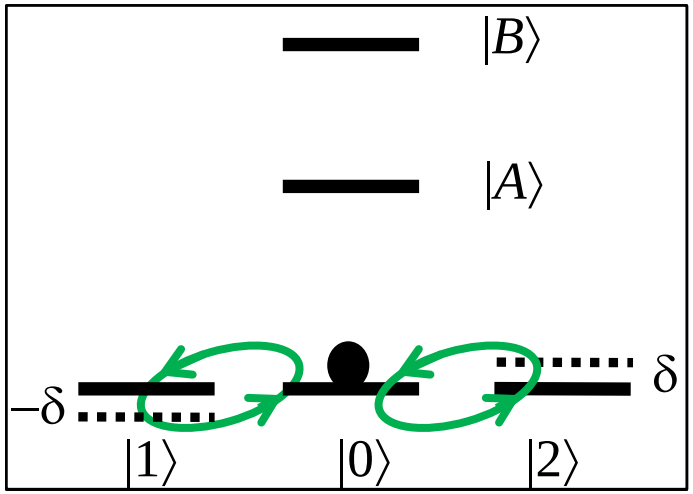


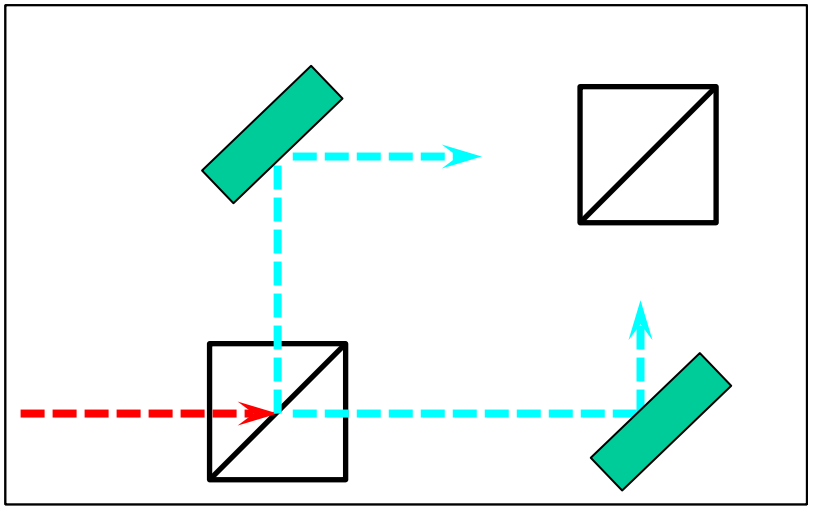
Interferometer based on Stored Spinor Slow Light





Interferometer based on Stored Spinor Slow Light





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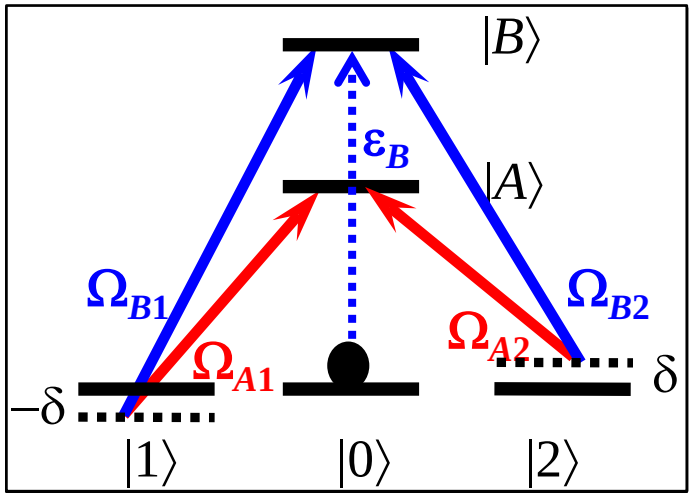

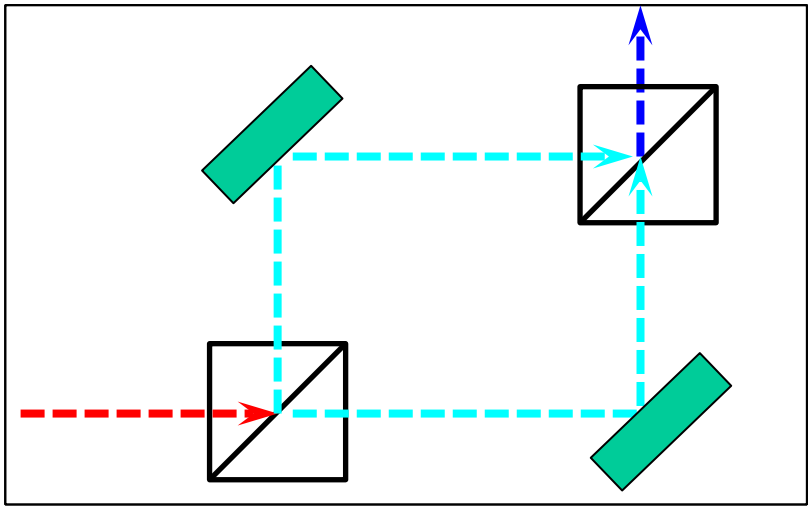

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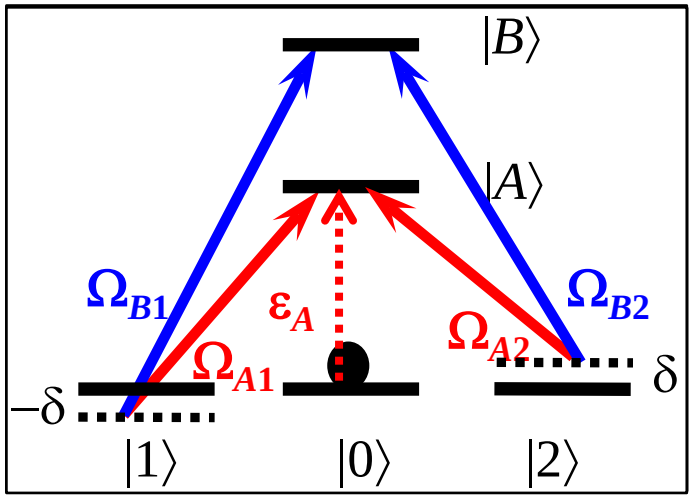
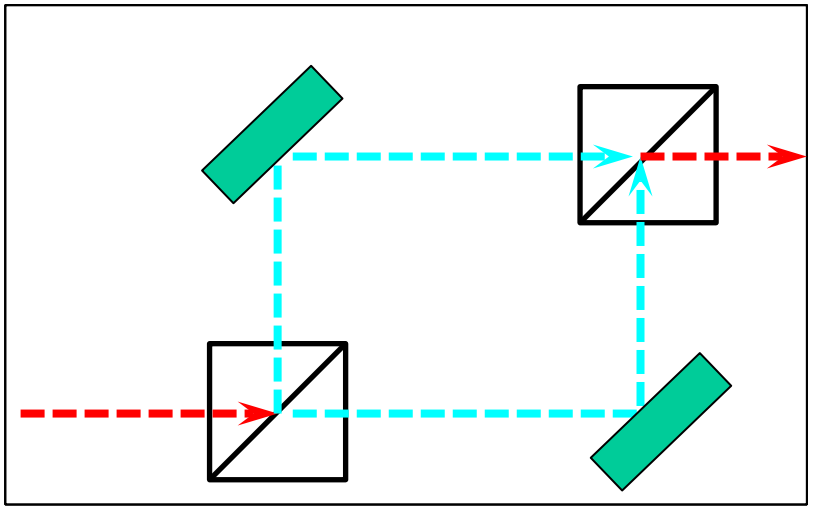
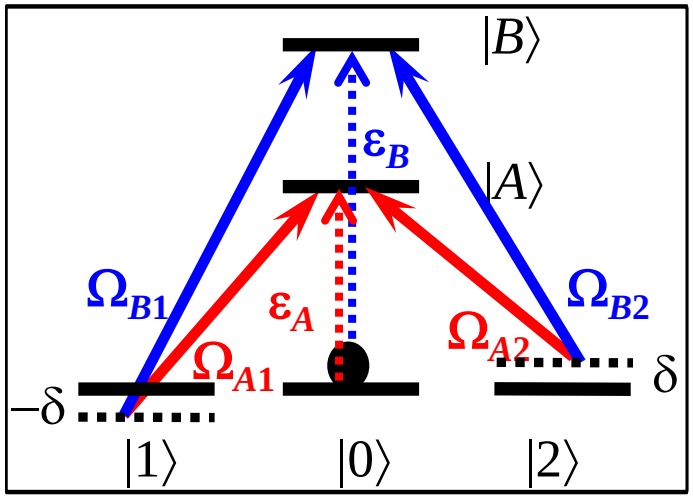
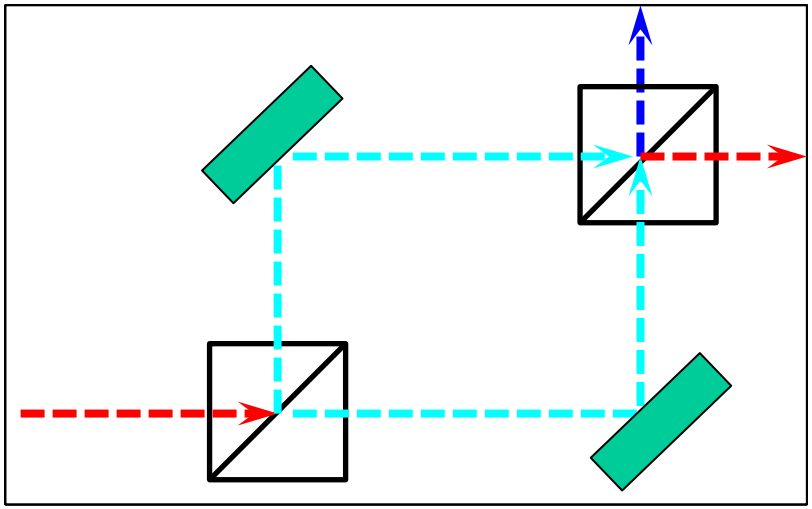


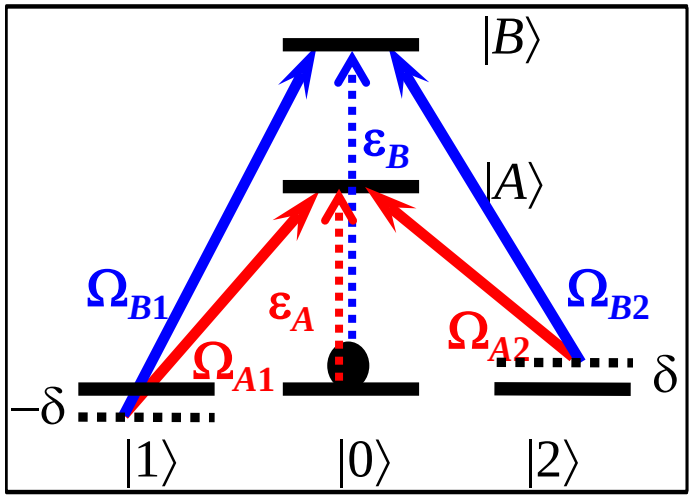


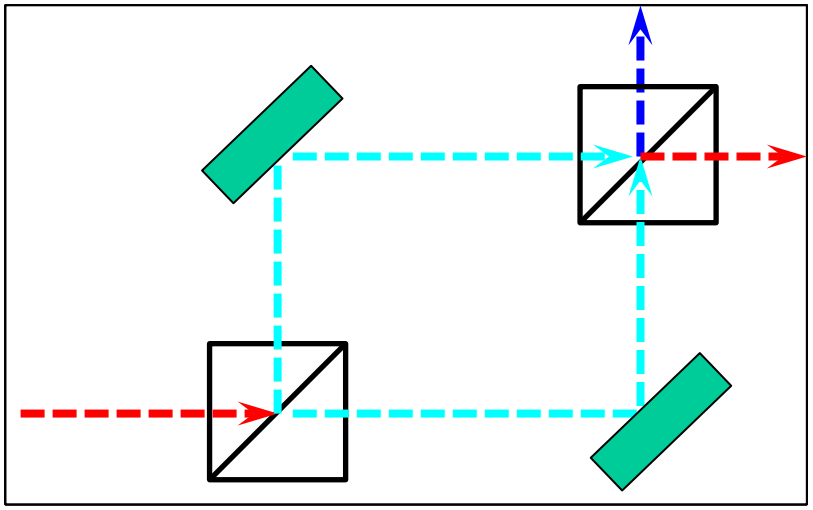
Interferometer based on Stored Spinor Slow Light



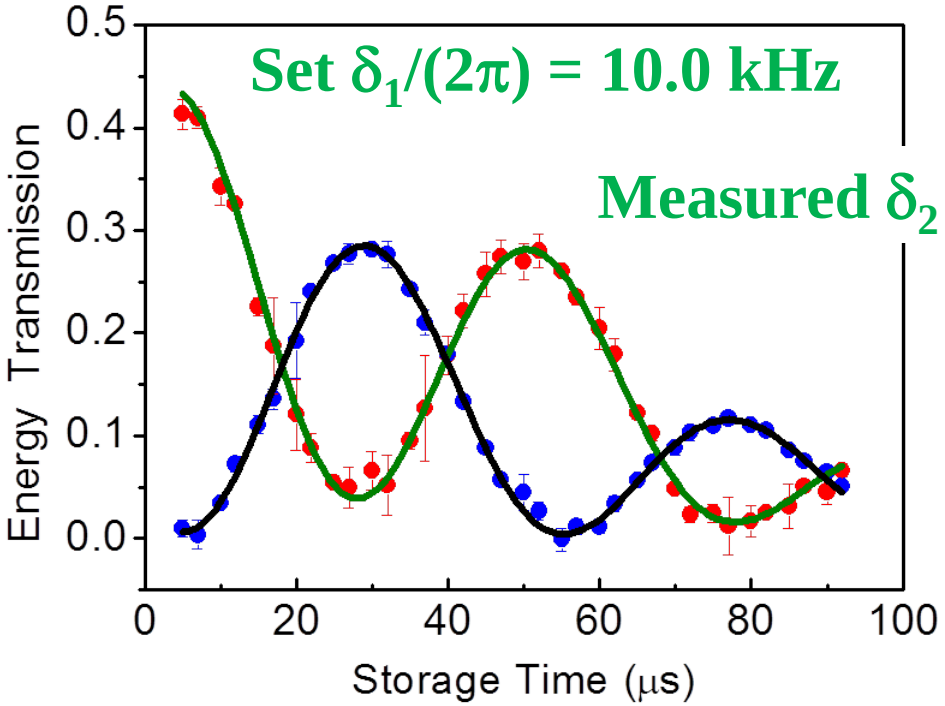


Interferometer based on Stored Spinor Slow Light

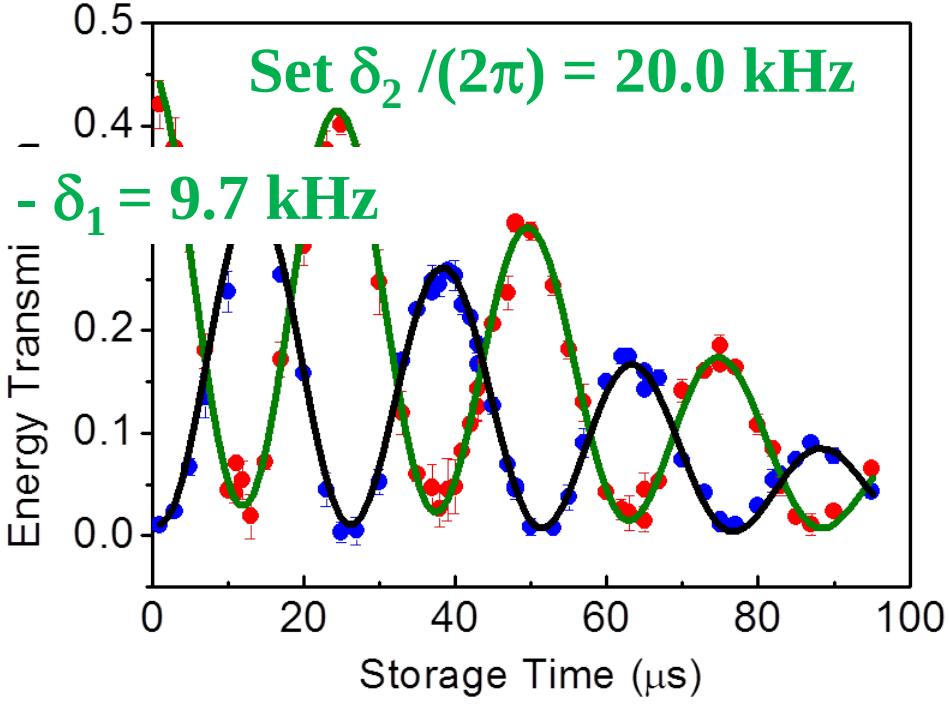




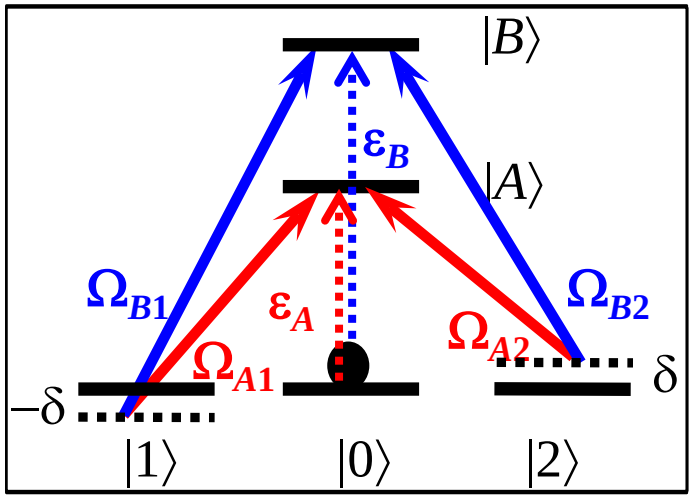
$\phi = \tau_s\delta$: fix δ and vary τ_s (the storage time).



Measured $\delta_2 - \delta_1$ = 9.7 kHz

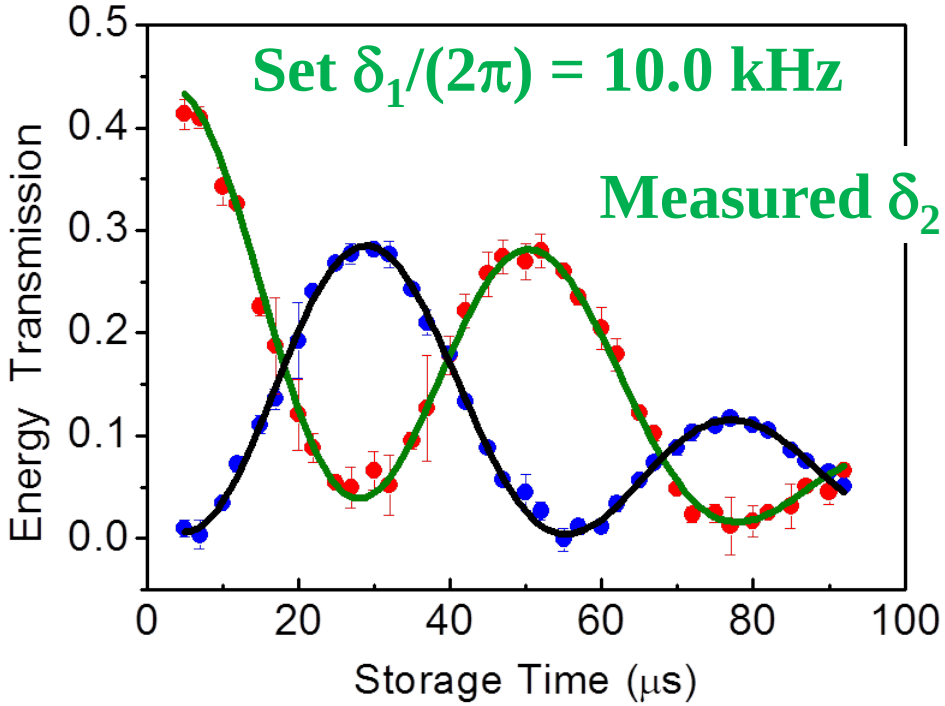


Interferometer based on Stored Spinor Slow Light

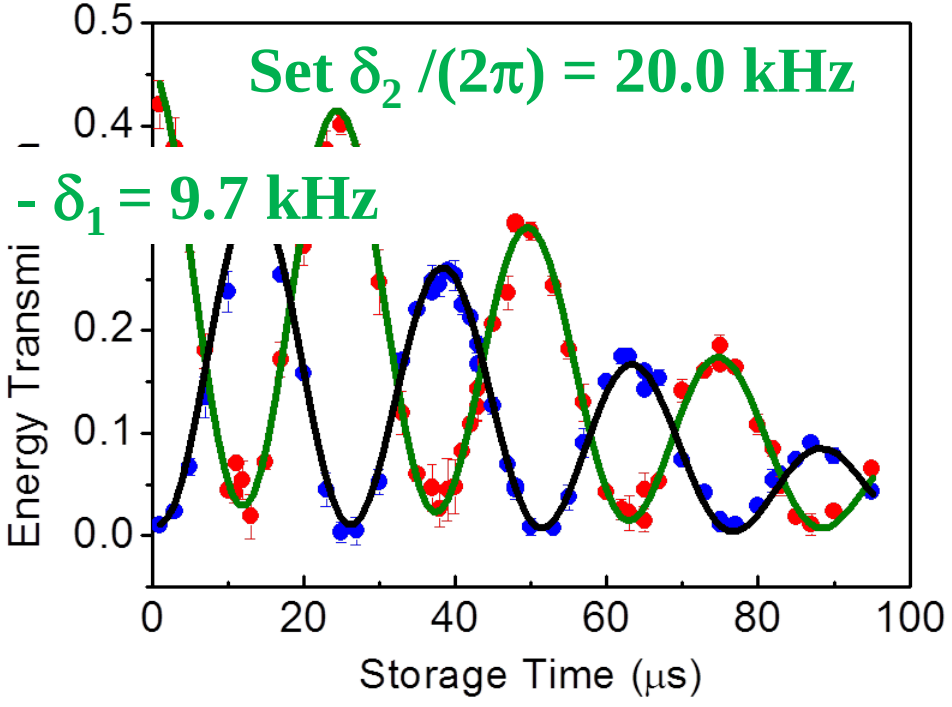


- A storage time ~ O(100μs) results in a precision ~ O(100Hz).
- The SSL interferometer can be used to detect two-photon detuning, Zeeman shift, AC Stark shift, etc.

$\phi = \tau_s\delta$: fix δ and vary τ_s (the storage time).



Measured $\delta_2 - \delta_1$ = 9.7 kHz

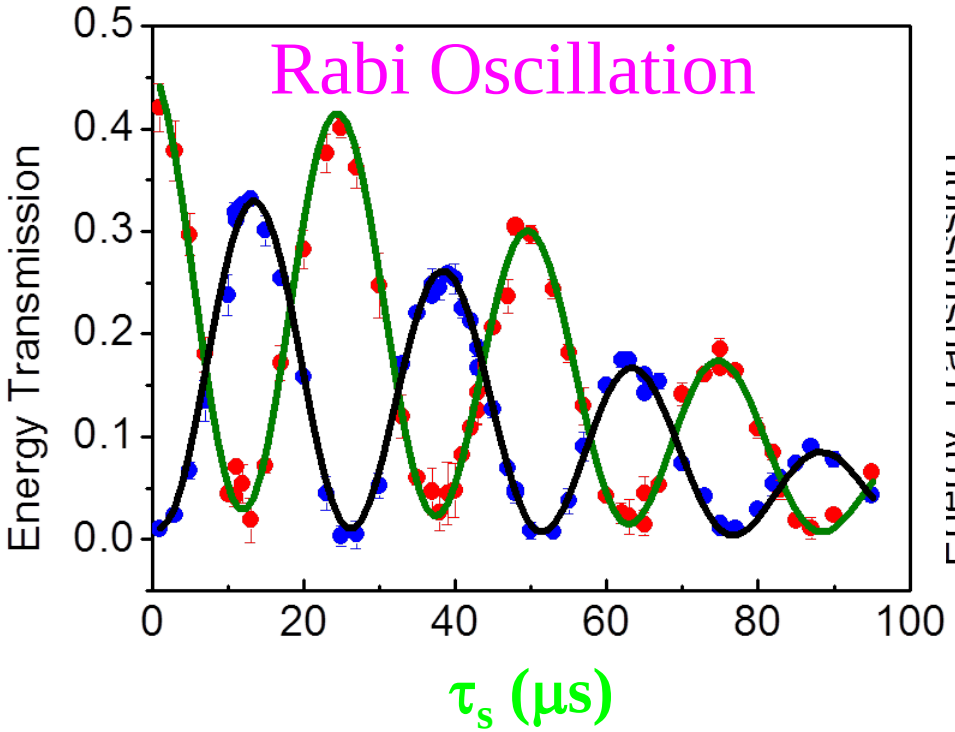


SSL as a Two-Color Qubit

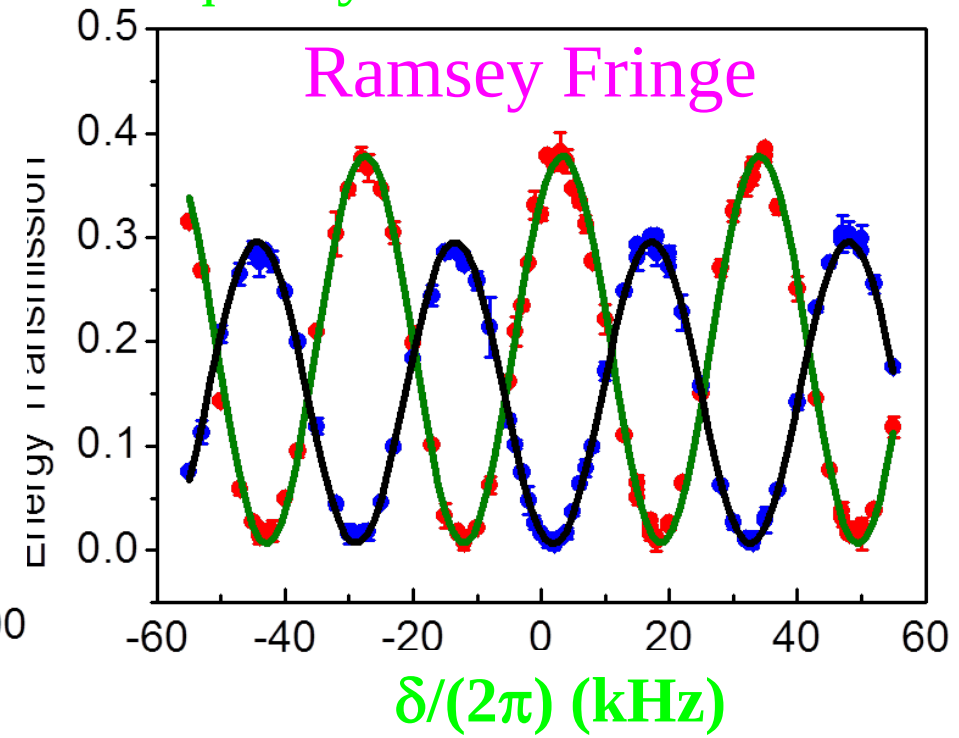
$$|\psi\rangle = \alpha\,|1_{\omega_A}, 0_{\omega_B}\rangle + \beta\,|0_{\omega_A}, 1_{\omega_B}\rangle$$

- Single-photon SSL is a qubit with the superposition state of two frequency modes. $(\alpha, \beta) = (\cos\phi, \sin\phi)$ and where $\phi = \tau_s\delta$.
- In long-distance quantum communication, photons of two-color quantum states are inert to the birefringent material, i.e. optical fibers.

Time-Domain Measurement

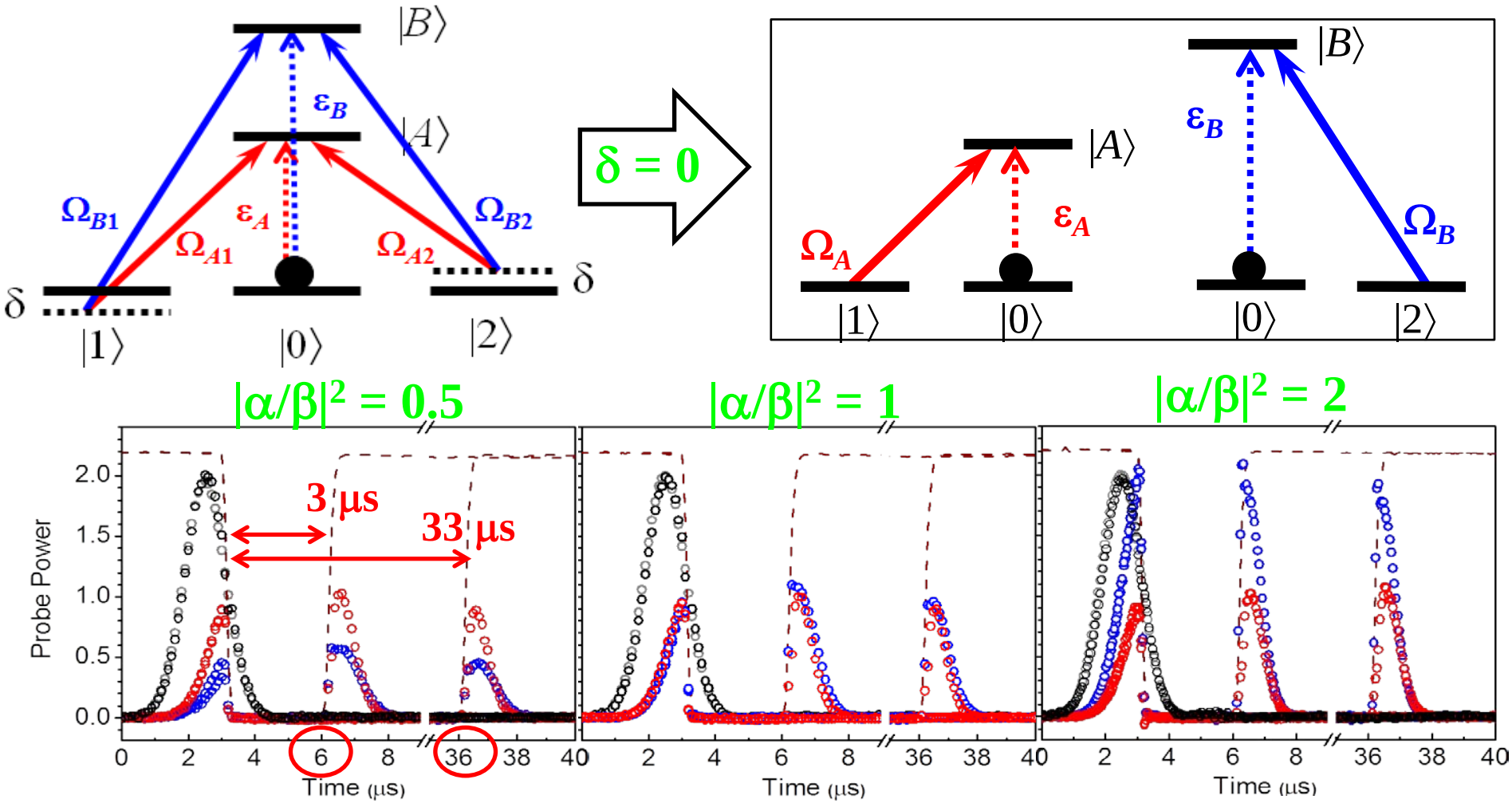


Frequency-Domain Measurement



Quantum Memory for SSL or Two-Color Qubits

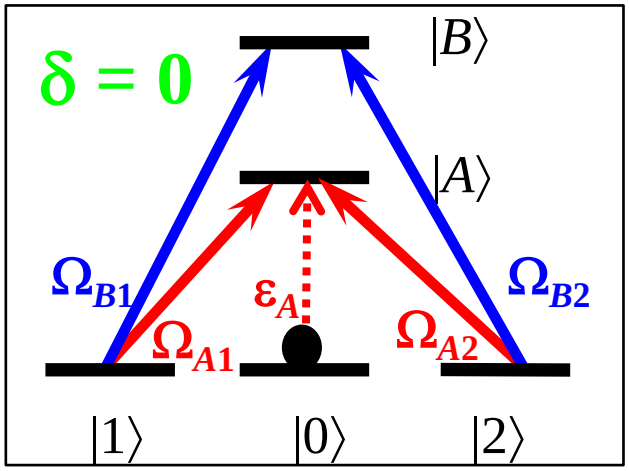
$$|\psi\rangle = \alpha\,|1_{\omega_A}, 0_{\omega_B}\rangle + \beta\,|0_{\omega_A}, 1_{\omega_B}\rangle$$

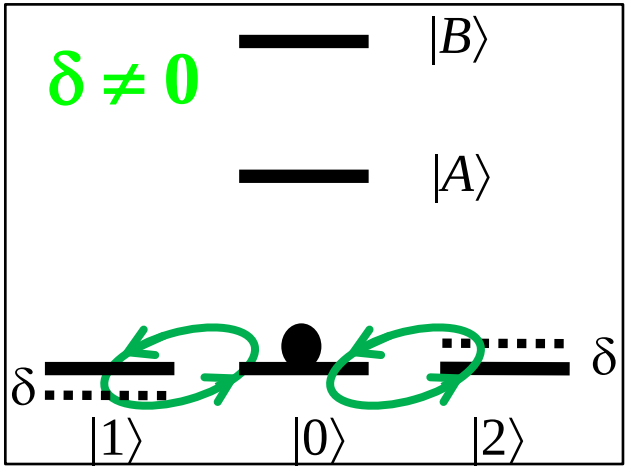


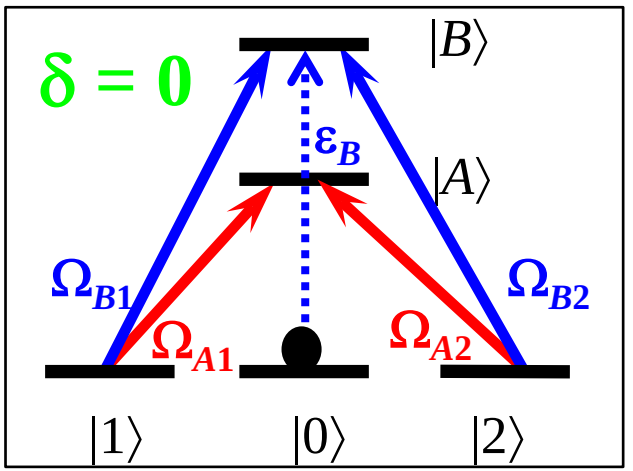
The shapes of the two retrieved pulses and their energy ratio after the storage time of 3 μs are very close to those after the storage time of 33 μs.

Quantum Rotator for SSL Qubits

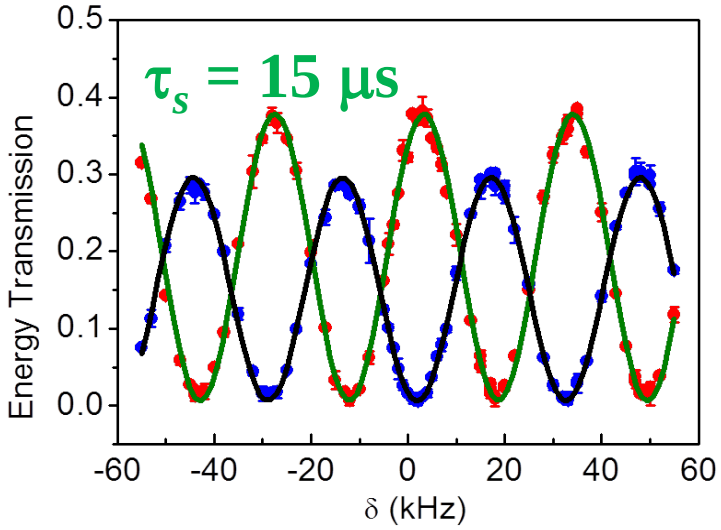
$$|\psi\rangle = \alpha\,|1_{\omega_A}, 0_{\omega_B}\rangle + \beta\,|0_{\omega_A}, 1_{\omega_B}\rangle$$







$(\alpha,\beta) = (1,0)$ ⟹



⟹ (0,1) or $(\cos\phi,\sin\phi)$ where $\phi = \tau_s\delta$

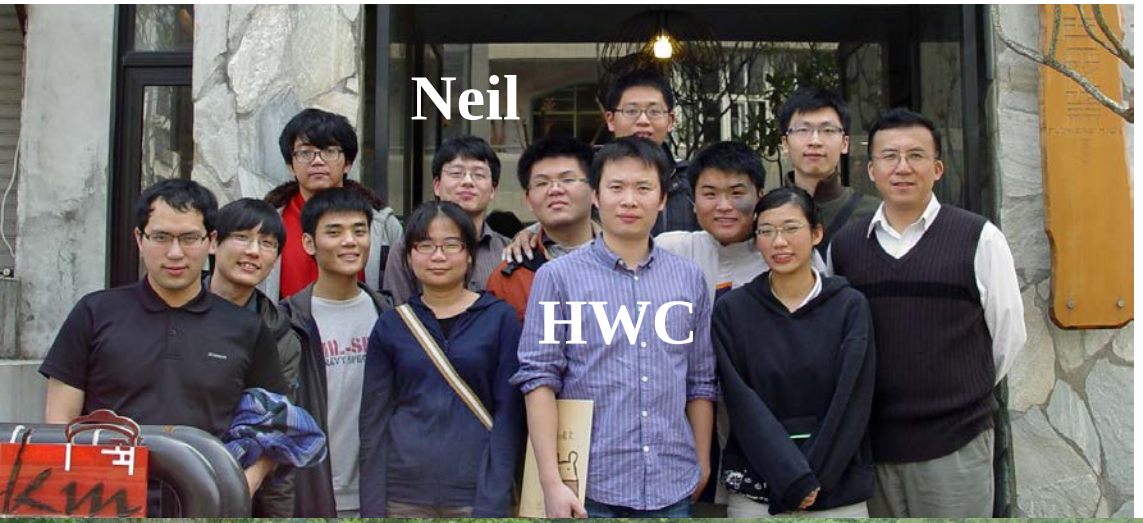
One can utilize a two-photon detuning (induced by the Zeeman or AC Stark shift) applied during the storage to change the α-to-β ratio.

Conclusion

- We report the first experimental demonstration of two-component or spinor slow light (SSL).
- In a proof-of-principle measurement, our data show that the stored SSL behaves like an interferometer for precise frequency determination.
- The double tripod scheme can lead to quantum memory for the two-color qubit, i.e. the superposition state of two frequency modes.
- In the nonlinear frequency conversion, the SSL is a better method than the widely-used double-Λ scheme.

M. J. Lee, J. Ruseckas, C. Y. Lee, V. Kudriasov, K. F. Chang, H. W. Cho, G. Juzeliunas, & IAY, **Nature Commun. 5, 5542 (2014).**

Acknowledgments $$$ MOST $$$ $$$ NTHU Top-Notch $$$



Collaboration Projects:

Taiwan-Latvia-Lithuania

&

EU FP7 COLIMA

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Meng-Jung Lee

Neil Lee

Kao-Fang Chang

Dr. Hung-Wen Cho

Vilnius U.

Gediminas Juzeliūnas

Julius Ruseckas

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