A Photon Echo-Based Quantum Memory Using Double Rephasing and Optical Locking

Byoung S. Ham

Inha University, S. Korea

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Experiments were performed by J. Hahn.

Motivation: Quantum memories
1. For scalable quantum nodes in quantum networks
2. For quantum repeaters in long-distance quantum communications

Physics: Coherent control of collective atom phases
1. Quantum mapping between optical and spin states
2. Double rephasing and optical locking

Optical locking:
-BS Ham, Nature Photon. **3**, 518 (2009)

Double rephasing:
-BS Ham, PRA **85**, 031402R (2012)

1. Background

2. Photon echoes
3. Modified photon echo protocols
4. Double rephasing & Optical locking

Functional Quantum Nodes:

1. Single photon generation, transmission/reception, and storage
2. Long-time storage for long-distance entanglement creation
3. Scalable

Remote Quantum Node Entanglement Creation:

1. Trapped single ion in an optical cavity: Nature **484**, 195 (2012)
2. Bulk solids: Nature Photon **6**, 234 (2012)

Constraint of Storage Time:

-Phase (spin) decay time: ~ms

To increase coherence (storage) time,

-Purely grown Isotopes: single spin (2012)

1. NV color center (^{13}C nuclear spin): 1.4 sec
2. ^{28}Si (nuclear spin): 180 sec

Trade-off: storage time vs. efficiency

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I. Quantum Memory

-Definition: Random quantum state storage and retrieval in a reversible manner

Trade-off: Efficient interface vs. Long-time storage

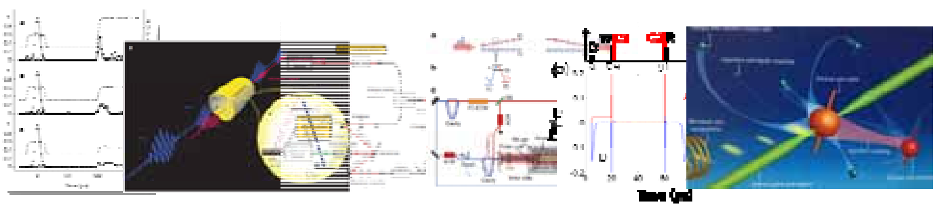
-History: Ensemble-based

-Early 2000s: Single mode

1. Slow light: Hau/Harris, Scully/Lukin, Hemmer/Ham, etc.
2. Raman: Polzik (2004)

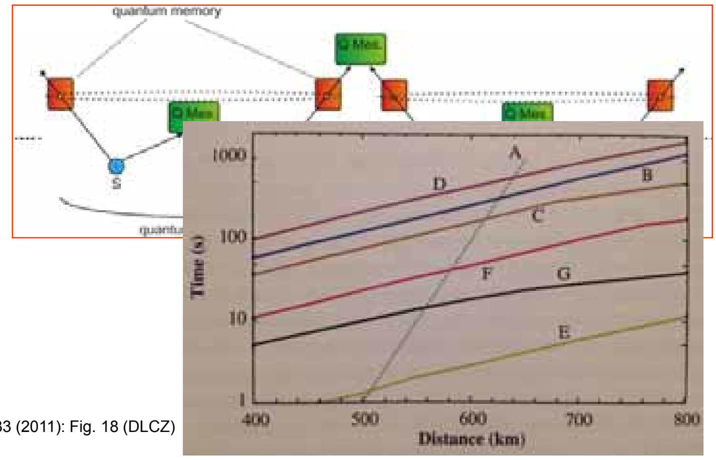
-Late 2000s: Multimode; Modified Photon echo, Spin echo

1. AFC:Gisin group
2. Gradient Echo: ANU group
3. Optically locked photon echo: Ham group
4. Spin echo in NV: Harvard/Stuttgart group



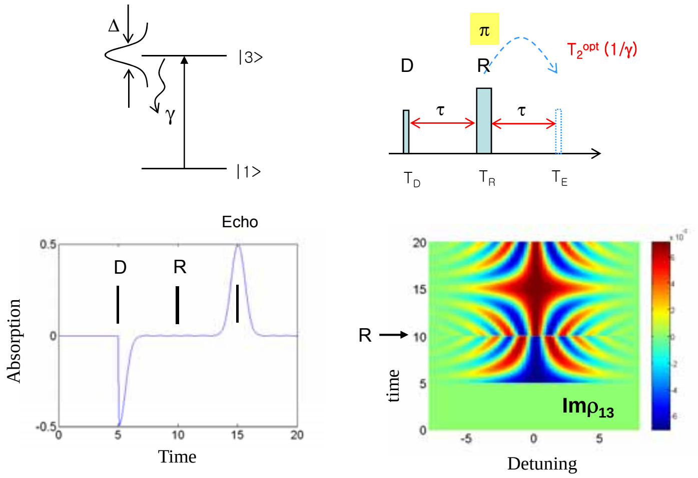
II. Why ultralong quantum memories?

- For distributed quantum networking
- For Long-distance quantum communications using quantum repeaters



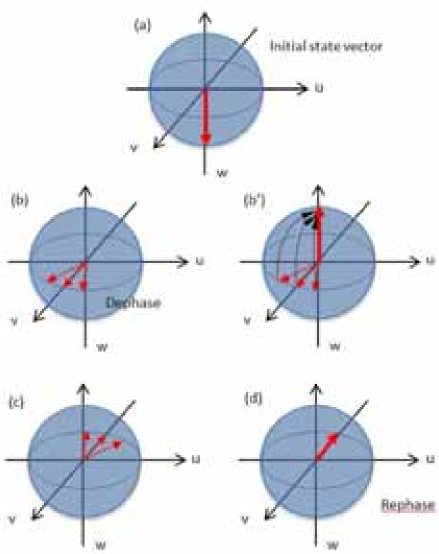
RMP 83, 33 (2011): Fig. 18 (DLCZ)

Two-Pulse Photon Echoes (2PE): Hahn Echoes

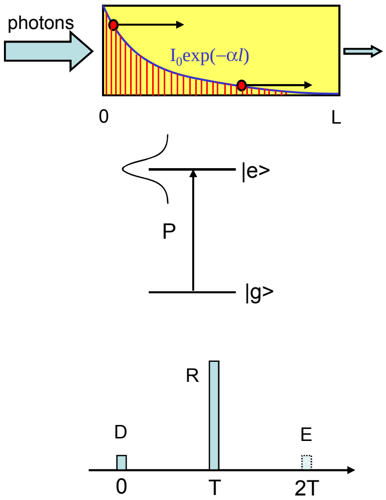


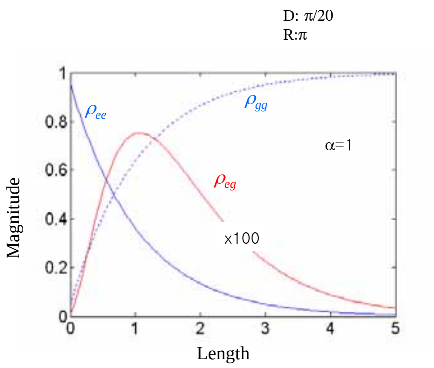
• Coherent transient process

Bloch Vector Model



Problem I: Echo reabsorption
→ η~1%



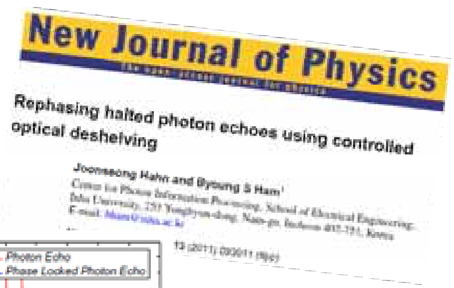


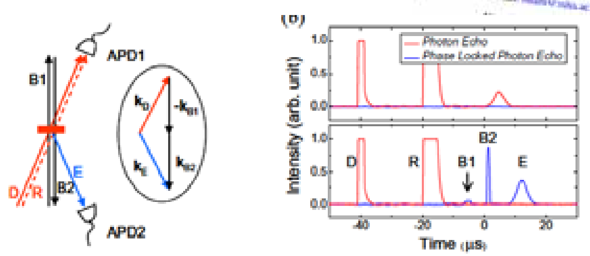
Storage vs. Retrival

Backward photon echo:

Theory:
- Moiseev & Kroll, PRL (2001)

Exp:
- Ham, NJP (2011)

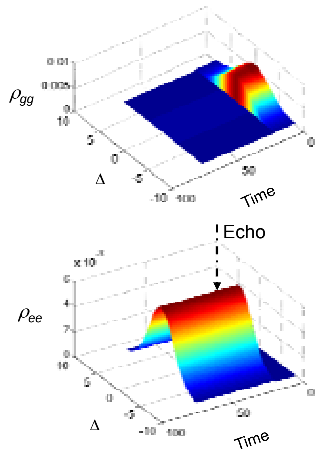

New Journal of Physics
Rephasing halted photon echoes using controlled optical deshelving
Joonseong Hahn and Byoung S Ham

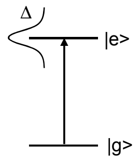


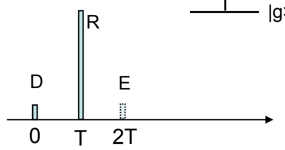
we conclude that the enhancement factor of 15 [2/(αβ)] is achieved due to backward propagation of E, where the echo E traces back mostly along

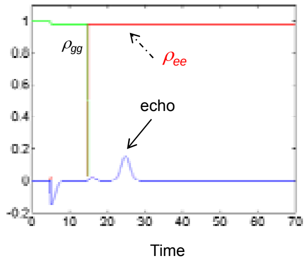
Problem 2: Population inversion

- Spontaneous emission: negligible!
- Stimulated echo gain: violation to 'no cloning'



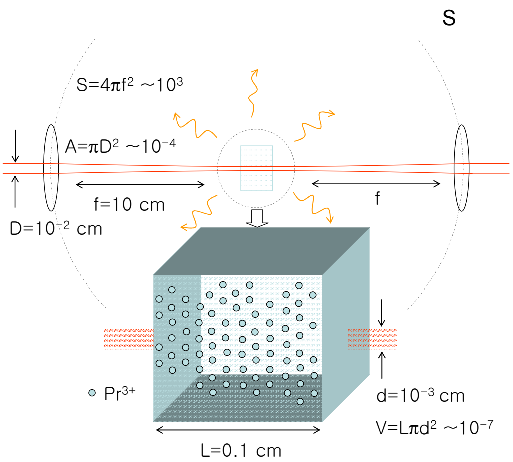






Spontaneous emission: negligible!

For a 0.1 ns data pulse,
spontaneously emitted photons in 0.05 at. % Pr doped YSO: 0.03



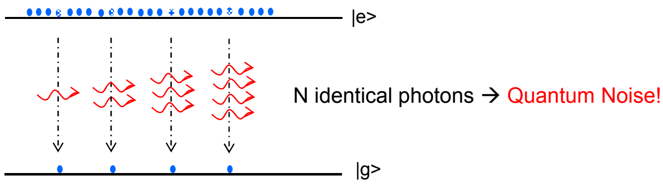
$N=VN_0 \sim 5\times10^{11}$.
$\eta=\Delta T/T_1 \sim 6\times10^{-7}$.
$N_e=\eta N=3\times10^5$.
$\alpha=A/S=10^{-7}$.

$N_f=\alpha N_e=\alpha\eta VN_0 \sim 0.03$

[Ham, JOSAB 29, 463 (2011)]

[Atom width: ~10 GHz]

Stimulated emission

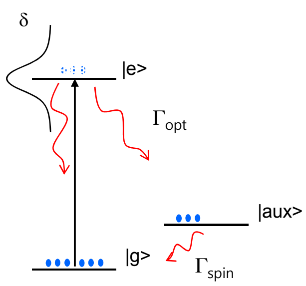


Violation to 'no cloning' theorem!

Solution for the population inversion:

-Deshelving: Atomic Frequency Comb (AFC)
-Linear Stark: Gradient echo
-Double Rephasing

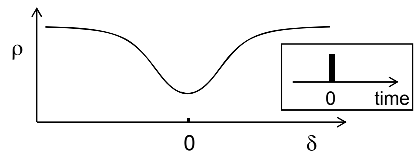
1. Spontaneous Deshelving: AFC



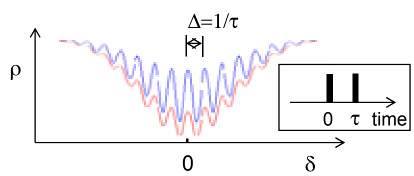
$\Gamma_{spin} << \Gamma_{opt}$; $\tau_{spin} >> \tau_{opt}$

In 1970's,
-To extend 2PE storage time!

A. With a single pulse:
- Wide pop excitation!

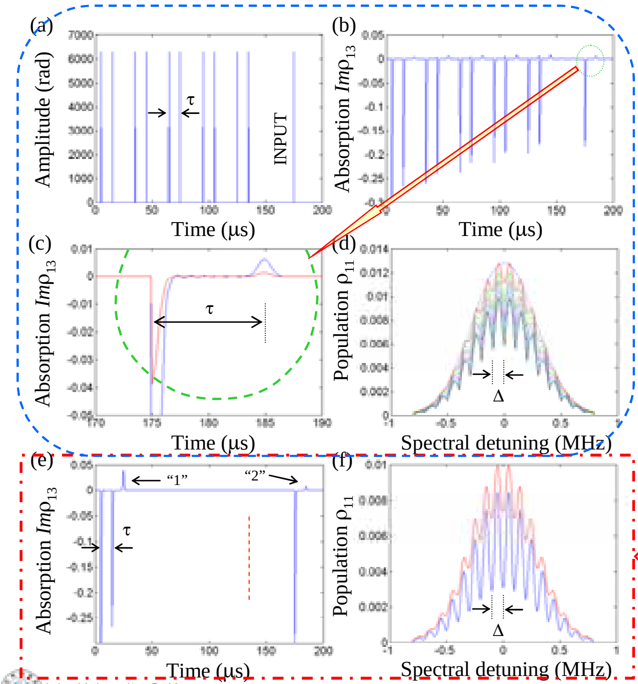


B. With delayed pulses by τ:
- Modulation spectrum!



→Population Grating → 3PE
→AFC

AFC vs. 3PE



AFC problem:
- Lower retrieval efficiency
- Short storage time: < 0.01 ms

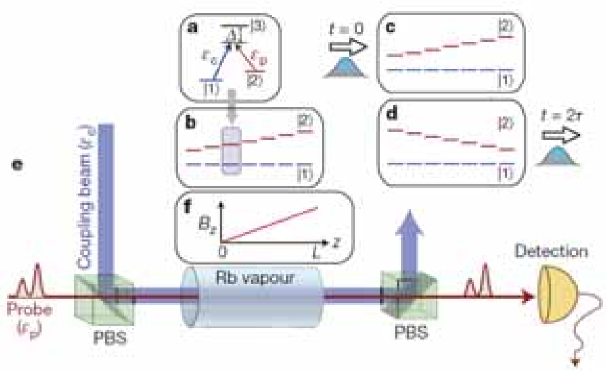
AFC

Δ=1/τ

Conventional Stimulated Echo (3PE)

[Ham, JOSAB **28**, 775 (2011]

2. Linear Stark Effect: Gradient Echo



Storage time: limited by T_2^{opt}

[Hosseini et al., Nature (2012)]
[Hetet et al, PRL (2008)]

3. Double Rephasing (with optical locking)

BS Ham, arXiv:1101.5480 (2011) → J-L Gouet *et al*, arXiv:1104.4875 (2011)

J-L Gouet *et al*, NJP (2011)

↓

No storage time extension!

↓

1. No population inversion
2. Storage time extension

Huge storage time extension up to spin T_1!

RAPID COMMUNICATIONS

PHYSICAL REVIEW A 85, 031402(R) (2012)

Coherent control of collective atom phase for ultralong, inversion-free photon echoes

Byoung S. Ham*

Center for Photon Information Processing, School of Electrical Engineering, Inha University, 253 Yonghyun-dong, Nam-gu, Incheon 402-751, South Korea

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To overcome the fundamental limitations of the π optical pulse-induced population inversion and optical decay-caused short storage time in conventional photon echoes, a coherent control of collective atoms is studied for inversion-free, optical decay-halted photon echoes, where the constraint of photon storage time is now replaced by a spin population decay process. Using phase-controlled double rephasing, an inversion-free photon echo scheme is obtained, where no spontaneous or stimulated emission-driven quantum noise exists. Thus, the present method can be applied for ultralong quantum memories in quantum repeaters for long-distance quantum communications.

DOI: 10.1103/PhysRevA.85.031402

PACS number(s): 42.50.Md, 82.53.Kp

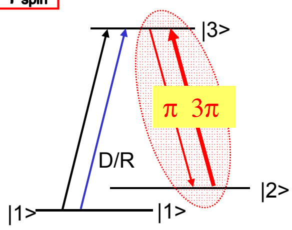
1. Background
2. Photon echoes
3. Modified photon echo protocols

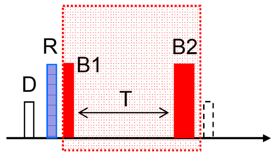
4. Double rephasing & Optical locking

1. Storage time extension: Optical locking

Coherence conversion into spin states

$\rho_{opt} \leftrightarrow \rho_{spin}$





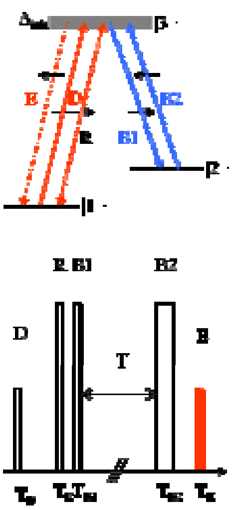
$\Phi_{B1} = (4n - 3)\pi$

$\Phi_{B2} = (4n - 1)\pi$

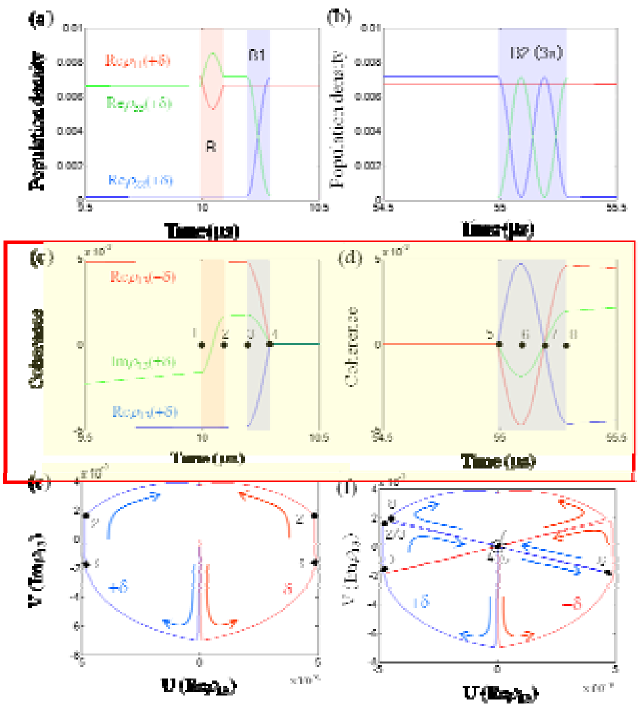
Optical coherence <-> **Spin coherence**

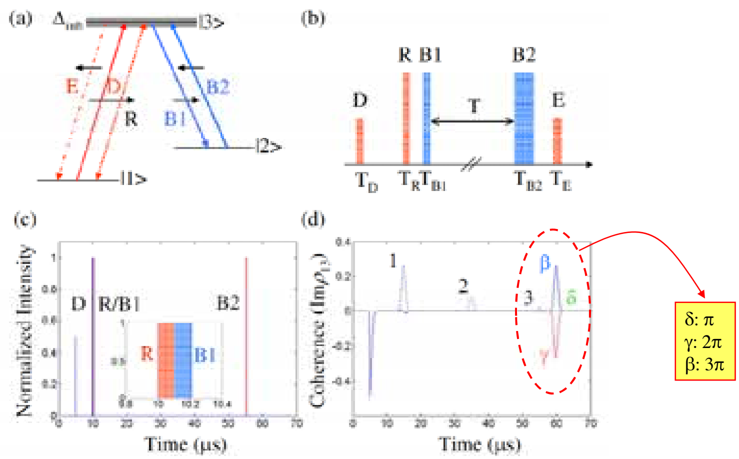
[Optical locking: Ham, Nature Photon. **3**, 518 (2009)]

[Ham, Opt. Exp. **18**, 1704 (2010)]
[Ham, NJP **13**, 093011 (2011)]



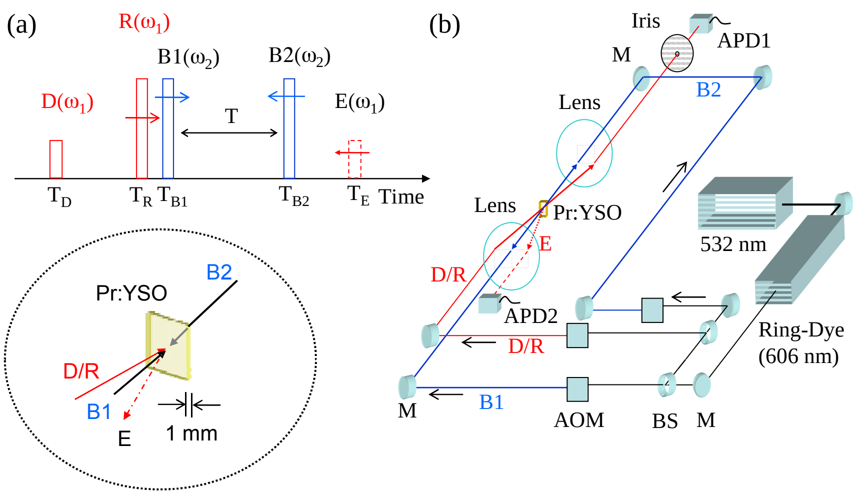
[Ham, Opt. Exp. **18**, 1704 (2010)]

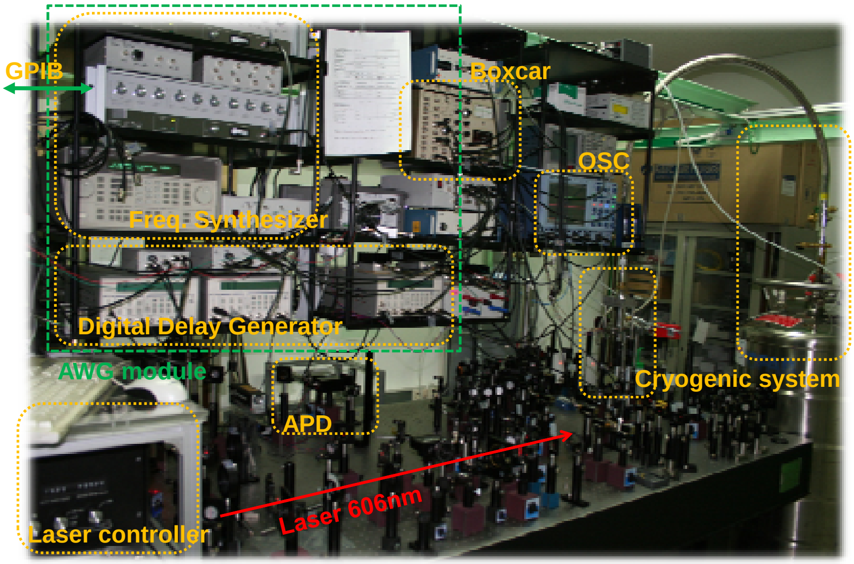




[B. S. Ham, Opt. Exp. **18**, 1704 (2010)]

Experimental Scheme





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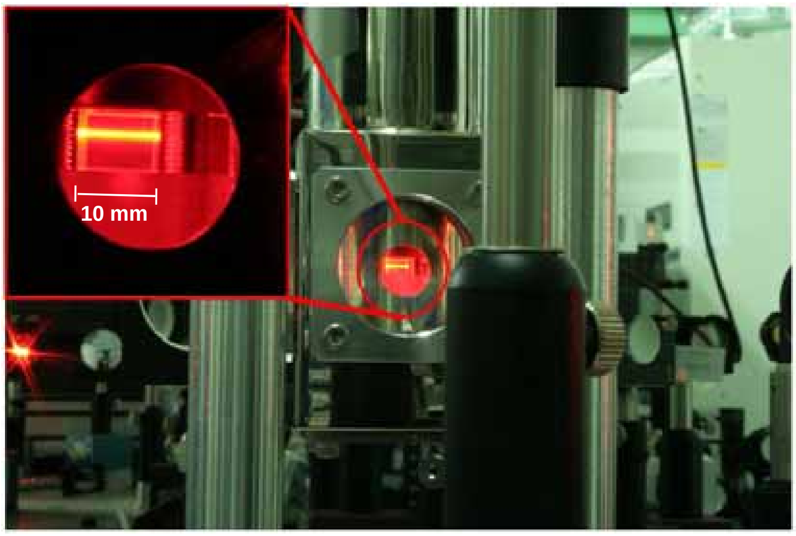
Pr^{3+}(0.05 at.%):YSO



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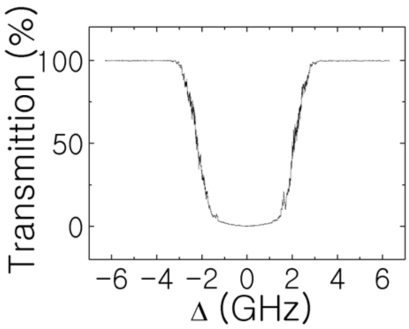
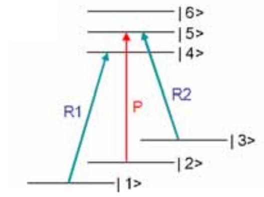
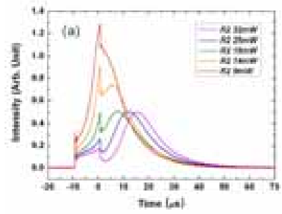
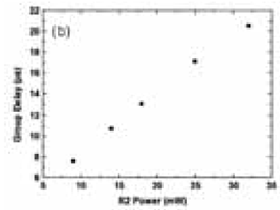
Pr^{3+}(0.05 at.%):YSO



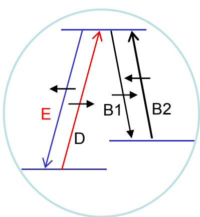




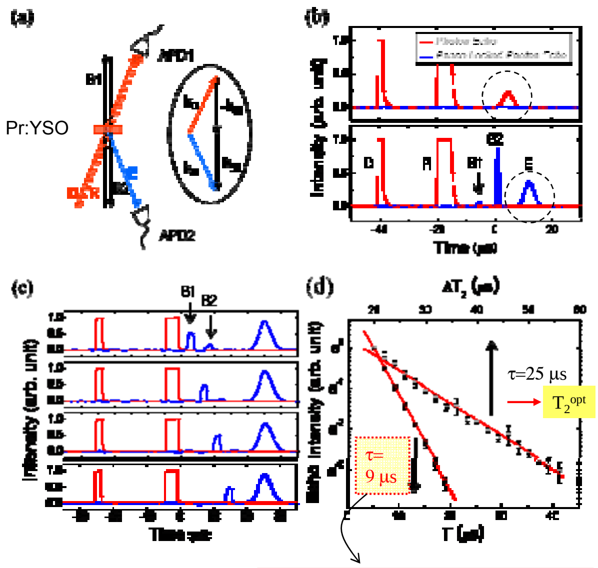


Optical depth: 1~30

Ham, OE 16, 16723 (2008)



2PE



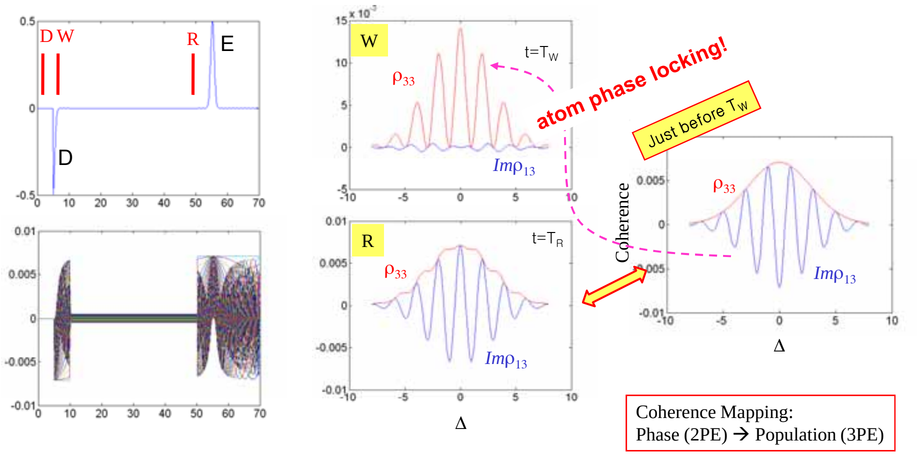
Backward echo scheme:
- echo enhancement: x15

Length: 1 mm → 3 mm
Enhancement: x15 → **x50**

[Ham, NJP **13**, 093011 (2011)]

Extended time: **spin dephasing!**

2. Three-pulse photon echo (3PE): population grating



Coherence Mapping:
Phase (2PE) → Population (3PE)

However, no practical benefit:

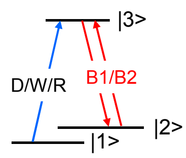
$T_2^{opt} \sim T_1^{opt}$ | $\rho_{ee} >> \rho_{gg}$

R: $\exp(i\delta t) \rightarrow \exp(-i\delta t)$

R

π pulse

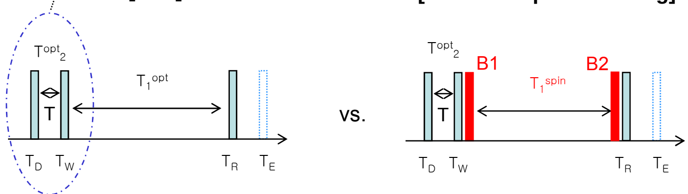
3. 3PE with optical locking



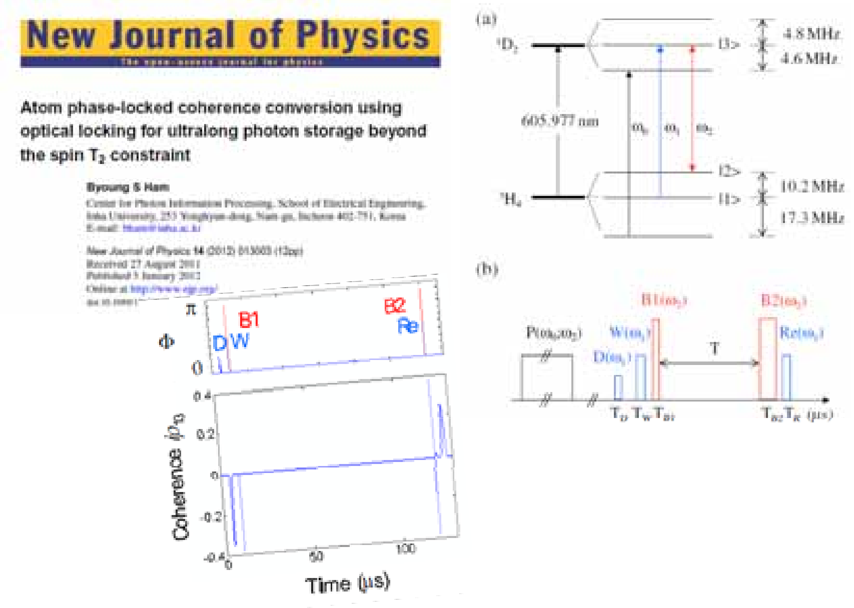
Atom Phase Locking: inherent property of 3PE

Active Optical Deshelving: Optical/spin coherence conversion

[3PE] vs. **[3PE with optical locking]**



[3PE]		[3PE with optical locking]
< 50% ($\rho_{33}>>\rho_{11}$)	**Efficiency**	~100 % ($T<<T^{opt}_2$)
T_1^{opt} (<<ms)	**Storage time**	T_1^{spin} (>sec)



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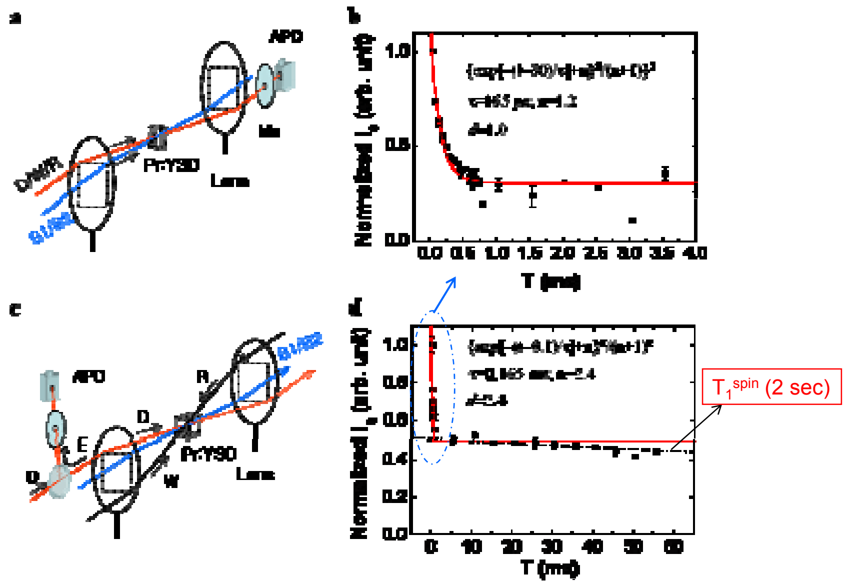

[Ham, NJP **14**, 013003 (2012)]

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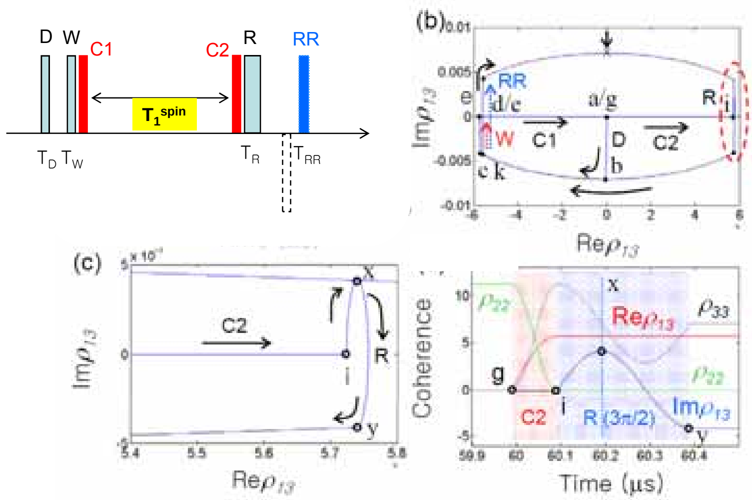
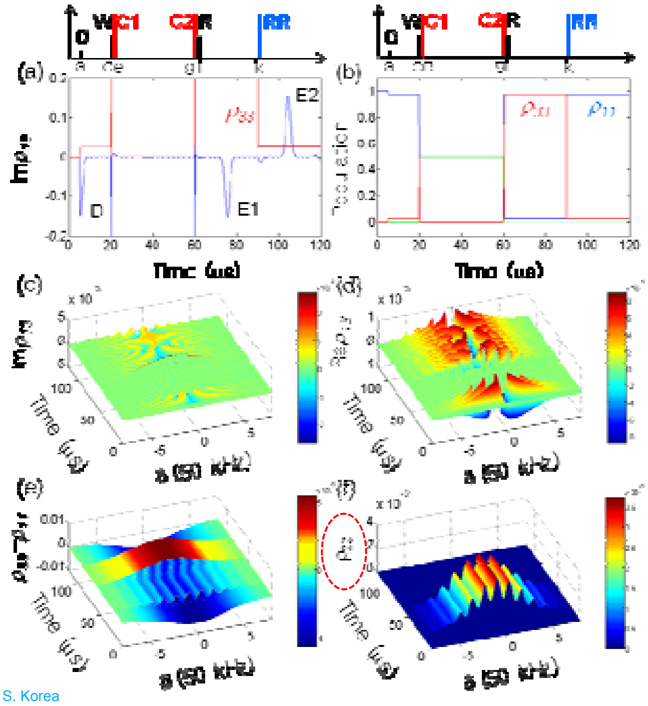
Problem:

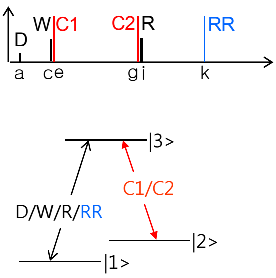
-Population inversion!

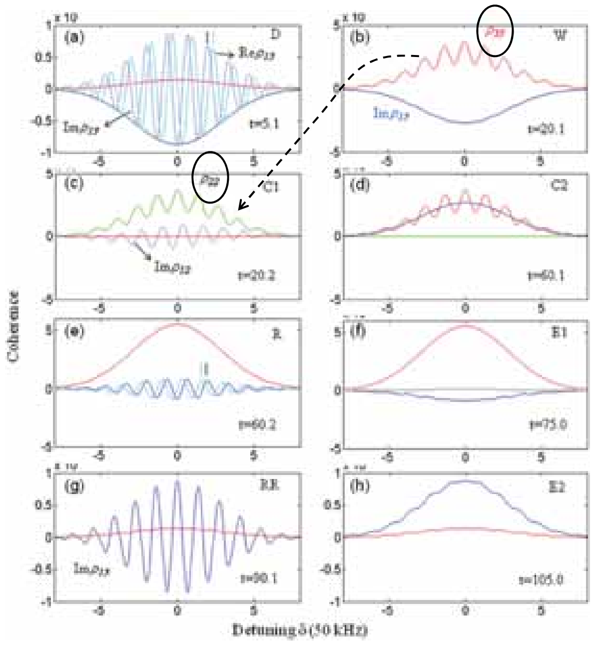
4. Double Rephasing



[Ham, PRA **85**, 031402(R) (2012)]







Optical phase grating → Spin pop. grating

[Ham, PRA **85**, 031402(R) (2012)]

Conclusion

- Presented double rephaisng via controlled deshelving
  to remove spontaneous emission noise or echo gain, and
  to extend photon storage time longer than a second.

Acknowledgment: Supported by
1. CRI program, MOST/NRF, S. Korea
2. Korea Communications Commission

Thank you for your attention!

http://photon.re.kr