Optimization of slow and stored light via EIT in atomic vapors

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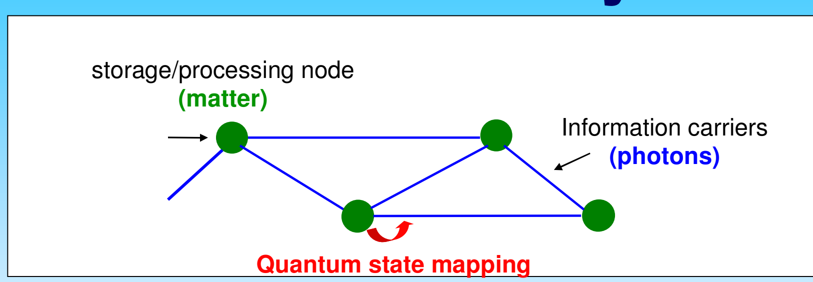
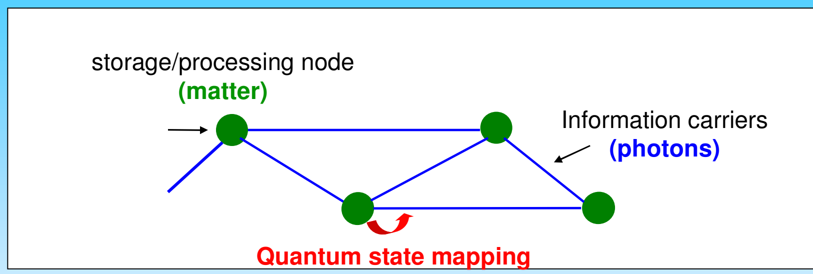
Quantum memory



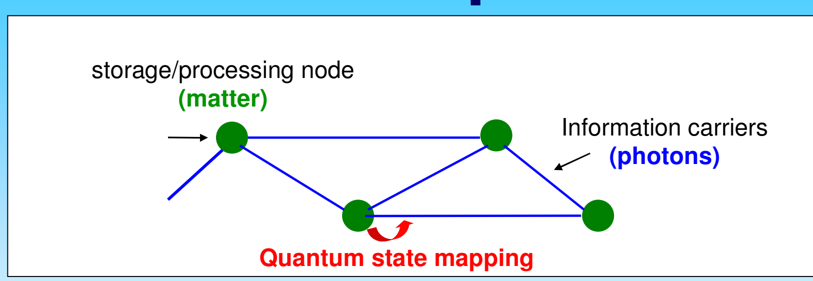
Challenge 1: design an efficient interface between photons and matter nodes

Quantum memory

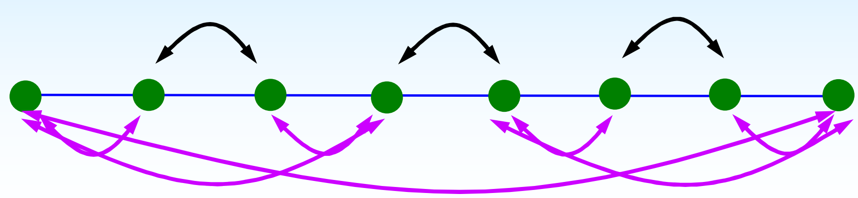


Challenge 2: generate nearly perfect entangled states between distant sites

Quantum repeater



Challenge 2: generate nearly perfect entangled states between distant sites



L. M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, Nature **414**, 413 (2001).

Quantum memory optimization

Atomic vapor cell

Cold atomic cloud

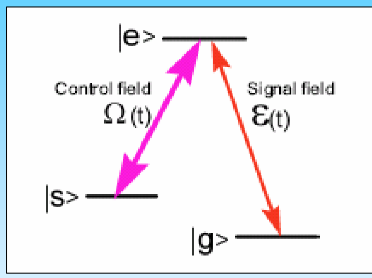
Impurities in solids

Photonic crystals

Outline

- Brief review of Electromagnetically Induced Transparency, and slow and stored light in atomic medium
- Optimization protocols for light storage:
  - iteration optimization procedure
  - optimal control field calculations
- Effect of four-wave mixing processes at higher optical depth
- Large fractional delay with EIT slow light using integrated gain and dynamic group velocity control

Light-atoms interaction: dark-state polariton



Strong coherent coupling between photonic and atomic quantum states

$$\hat{\Psi} = \cos\theta\ \hat{\mathcal{E}} - \sin\theta\ \sqrt{N}\hat{\sigma}_{gs}$$

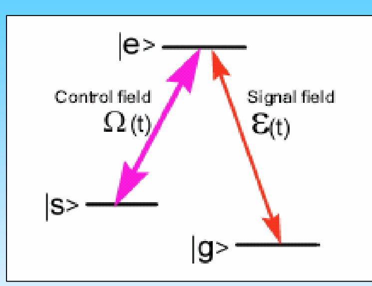
$$\cos\theta = \frac{\Omega}{\sqrt{\Omega^2 + g^2 N}} = \sqrt{\frac{v_g}{c}}$$

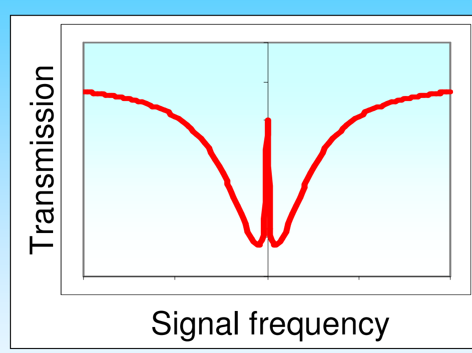
Photons of the probe field

Excitations of the spin wave

M. Fleischhauer and M.D. Lukin PRL 84, 5094 (2000)

Electromagnetically Induced Transparency (EIT)





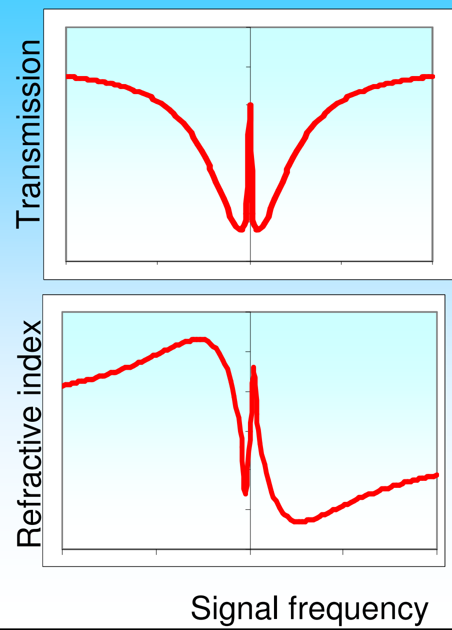
Dark states:

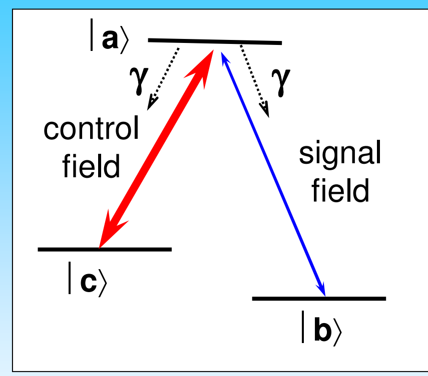
$$|D\rangle = \frac{\mathcal{E}|c\rangle - \Omega|b\rangle}{\sqrt{\mathcal{E}^2 + \Omega^2}}$$

EIT width

$$\gamma_{EIT} = \frac{|\Omega|^2}{\sqrt{\gamma g^2 N k L}}$$

Slow light in EIT

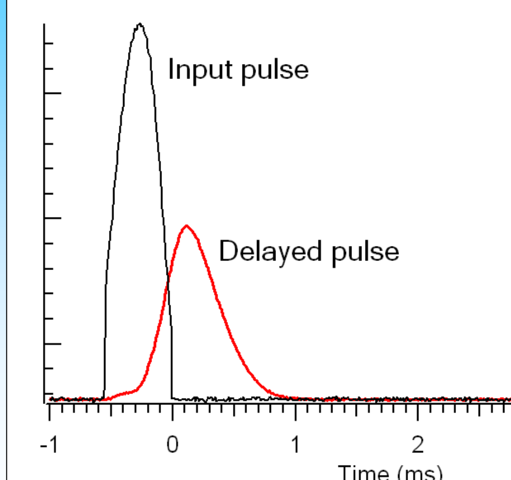




Group velocity

$$v_g = \frac{c}{1 + g^2 N / |\Omega|^2}$$

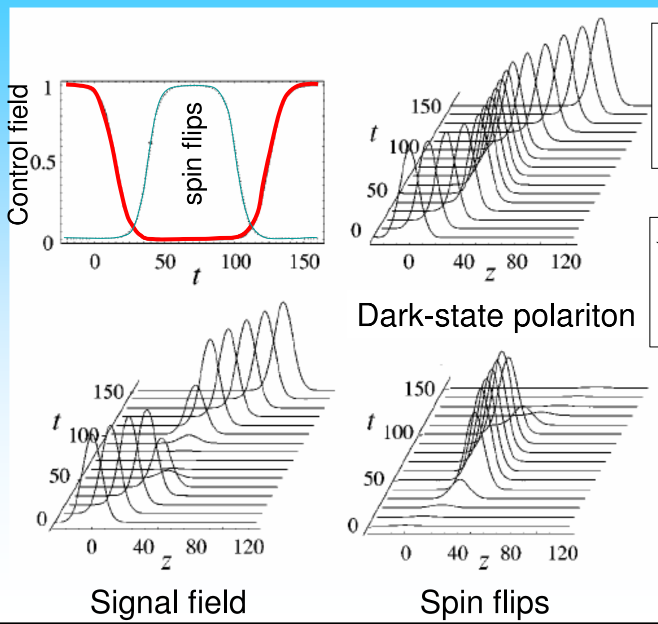
Slow light in EIT



Group velocity

$$v_g = \frac{c}{1 + g^2 N / |\Omega|^2}$$

Stored light in EIT



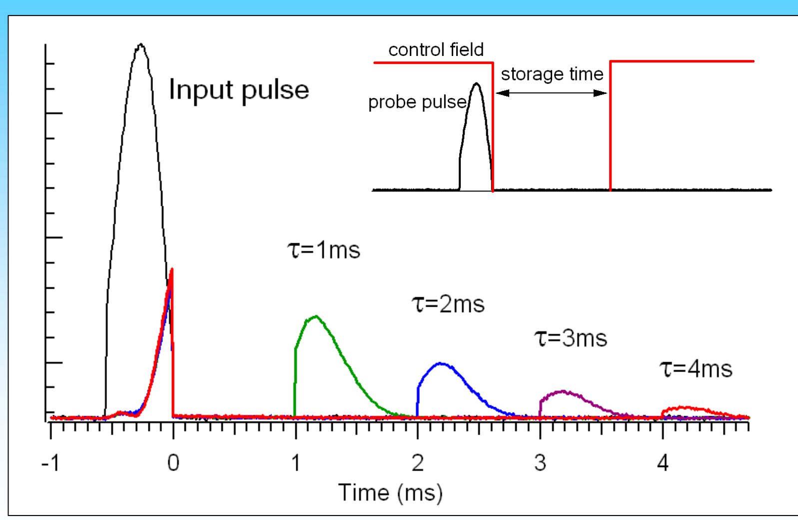
Group velocity

$$v_g = \frac{c}{1 + g^2 N / |\Omega|^2}$$

$$\hat{\Psi} = \cos\theta\ \hat{\mathcal{E}} - \sin\theta\ \sqrt{N}\hat{\sigma}_{gs}$$

$$\cos\theta = \sqrt{\frac{v_g}{c}}$$

Stored light in EIT



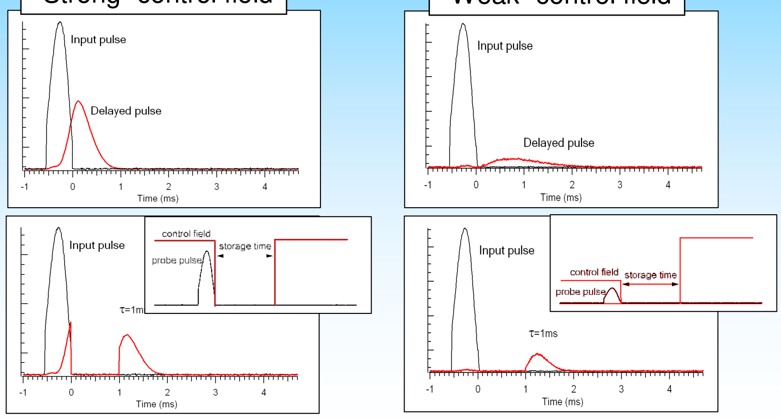
Finite optical depth

$$v_g = \frac{c}{1 + g^2 N / |\Omega|^2},$$

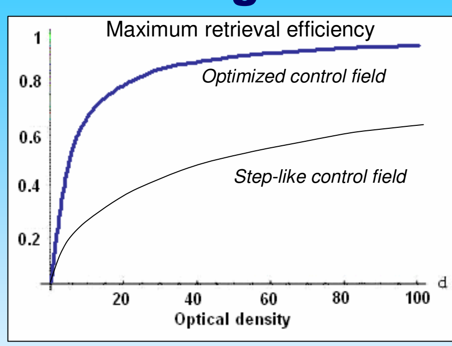
$$\gamma_{EIT} = \frac{|\Omega|^2}{\sqrt{\gamma g^2 N / L}},$$

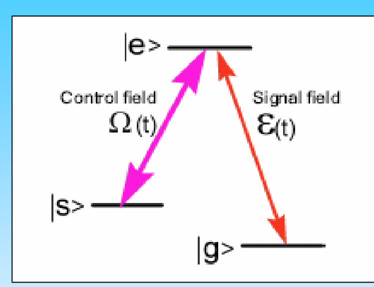
"Strong" control field

"Weak" control field



Stored light efficiency optimization

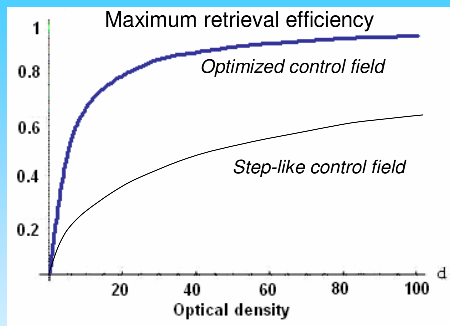


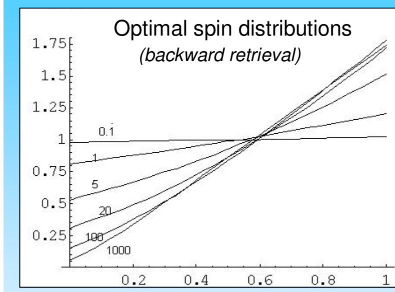


- Maximum storage and retrieval efficiency depends only on optical density of a medium and retrieval direction.

A.V. Gorshkov *et al.*, Phys. Rev. Lett. 98, 123601 (2007);
A.V. Gorshkov *et al.*, Phys. Rev. A **76**, 033804,033805, 033806 (2007) .

Stored light efficiency optimization





- Maximum storage and retrieval efficiency depends only on optical density of a medium and retrieval direction.
- There exist a unique spin coherence distribution which provides maximum storage efficiency.

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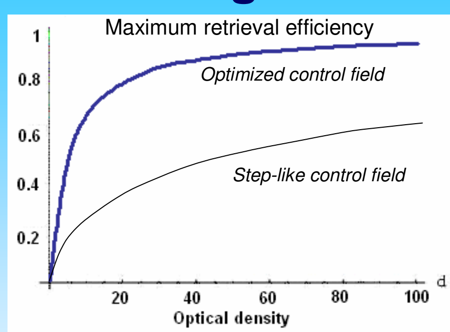
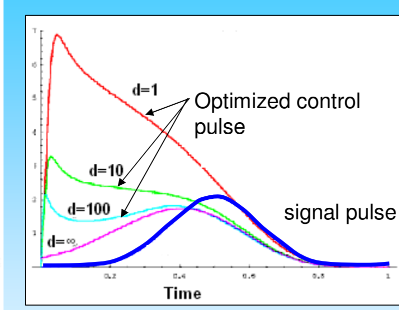
Stored light efficiency optimization

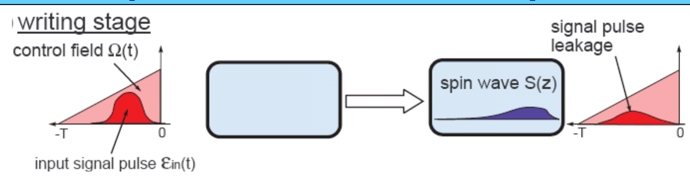




- Maximum storage and retrieval efficiency depends only on optical density of a medium and retrieval direction.
- There exist a unique spin coherence distribution which provides maximum storage efficiency.
- For each signal pulseshape there is a corresponding control field pulseshape which maps the signal pulse into optimal spin distribution.

A.V. Gorshkov *et al.*, Phys. Rev. Lett. 98, 123601 (2007);
A.V. Gorshkov *et al.*, Phys. Rev. A **76**, 033804,033805, 033806 (2007) .

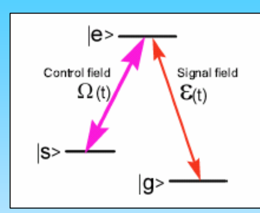
Optimization via time reversal (forward retrieval)



The optimal **signal** pulse for a **given control** field shape can be found experimentally by starting with an arbitrary pulse, and cycling through storage and retrieval procedure several times.

Is this procedure useful in real life?

<u>Assumptions of the theory:</u>
Three-level Λ system
No spin wave decay
Motionless atoms
Uniform control field intensity across the laser beam

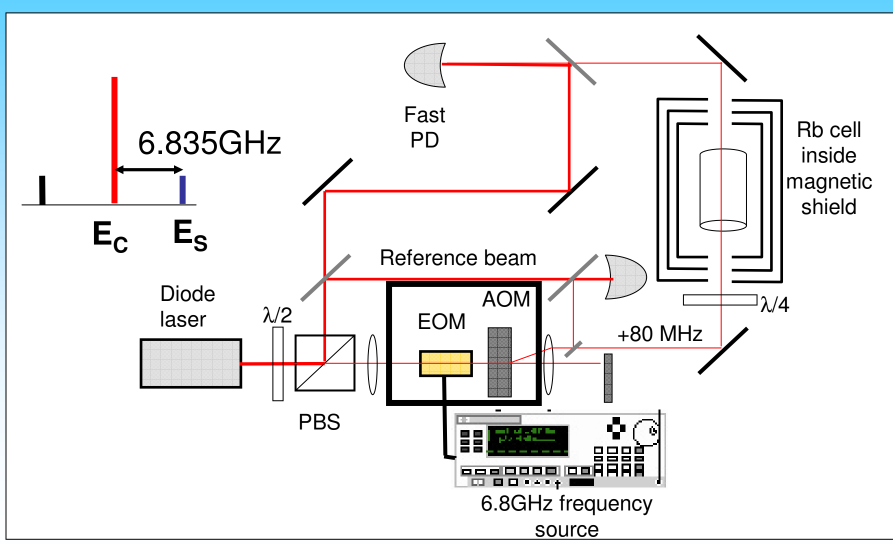


<u>Realities of the experiment:</u>
Multilevel Rb atoms
Nonzero spin wave decay
Doppler and pressure broadening of optical transition
Velocity changing collisions with buffer gas atoms
Gaussian laser beam crossection
...

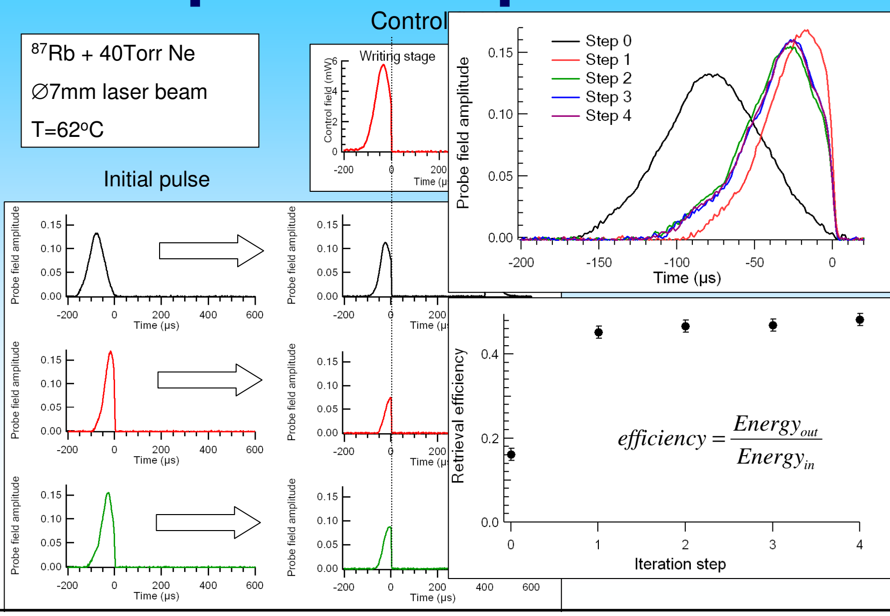
What we need to test:

Statement I: After a few iterations a signal pulse shape will converge
Statement II: Final converged signal pulse is stored and retrieved with the highest efficiency
Statement III: For the same control field a signal pulse should converge to the same optimal shape independent of the initial signal pulse shape
Statement IV: Each control field profile results in different optimal signal pulseshape, but for each control-signal pair maximum achievable efficiency is the same.

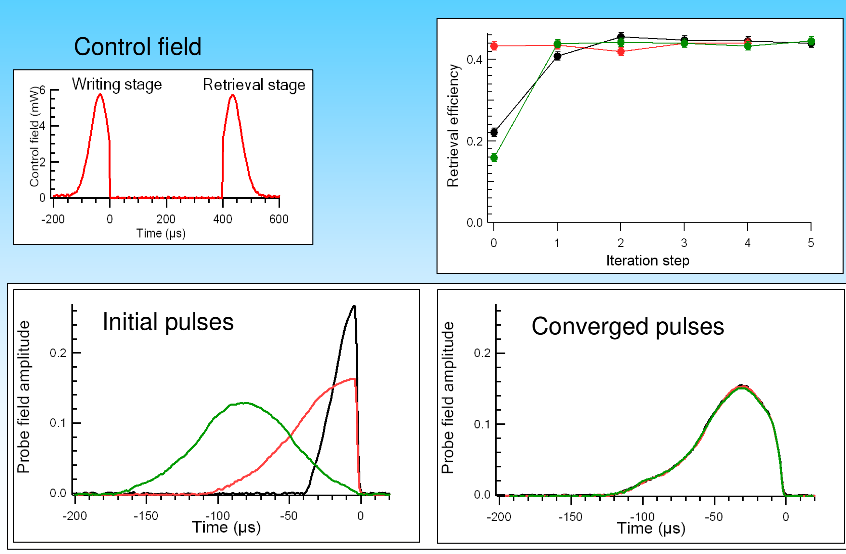
Experimental setup



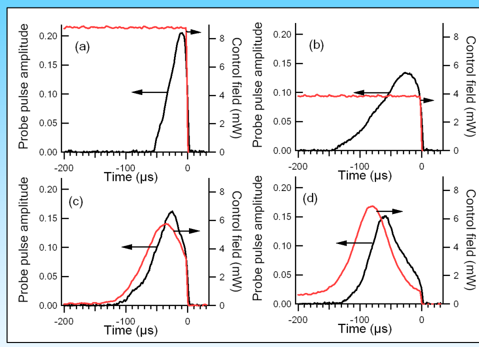
Optimization procedure

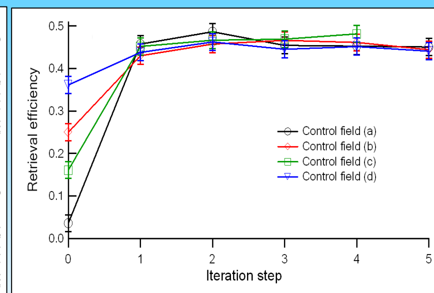


Different initial pulses



Different control field profiles

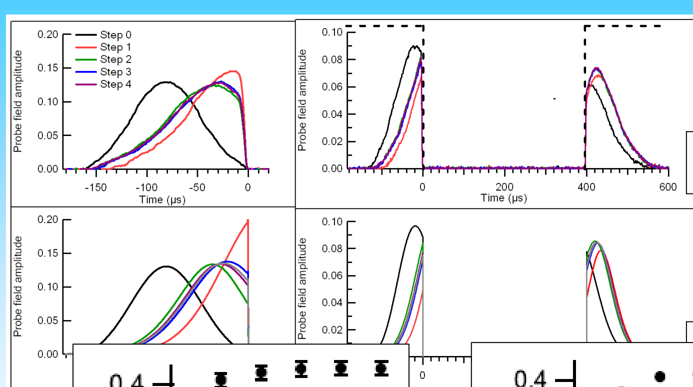




An optimized signal pulse shape is unique for each control field…

… but they all converged to the same maximum retrieval efficiency

Comparison with theory

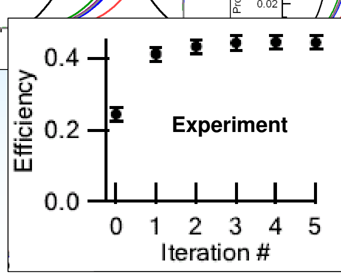


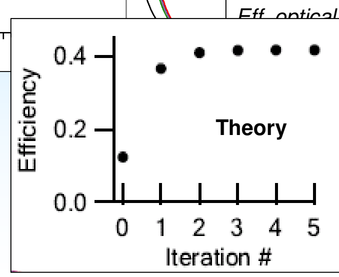
Experiment

control field flat 3.8mW
T=62 °C

Simple 3-level system

Eff. optical depth =9





What we've tested:

✓Statement I: After a few iterations a signal pulse shape <u>does</u> converge

✓Statement II: Final converged signal pulse is stored and retrieved with the highest efficiency.

✓Statement III: For the same control field a signal pulse converges to <u>the same</u> optimal shape independent of the initial signal pulse shape

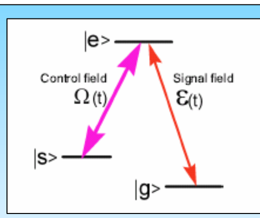
✓Statement IV: Each control field profile results in different optimal signal pulseshape, but for each control-signal pair maximum achievable efficiency is the same.

only while pulse duration is small compare to the spin wave decay time

I. Novikova *et al.*, Phys. Rev. Lett. 98, 243602 (2007)

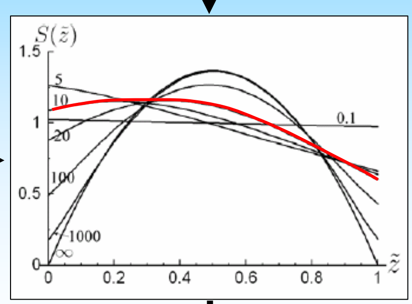
Calculations of optimal control field

For a **given signal** field pulseshape we can calculate the **control** field temporal profile that provides the most efficient mapping between the input pulse and an optimal spin wave .



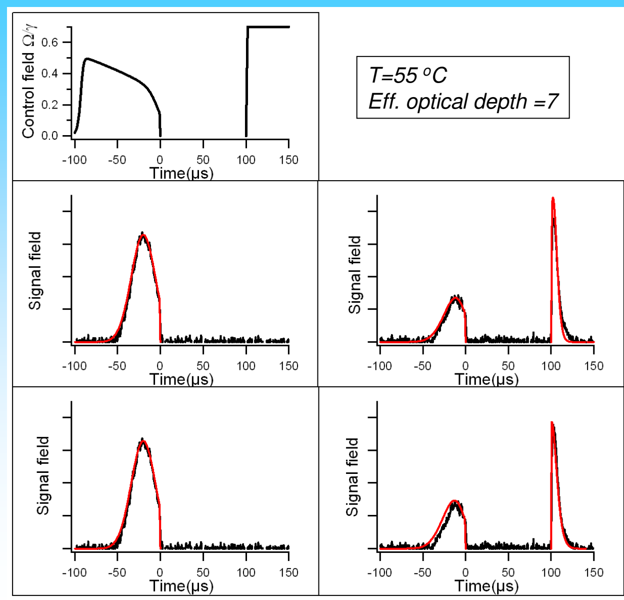
Input signal field $\mathcal{E}_{in}(t)$

Calculate effective optical depth ***d***



Optimal control field Ω(t)

Control field optimization



Measured efficiency – 0.35

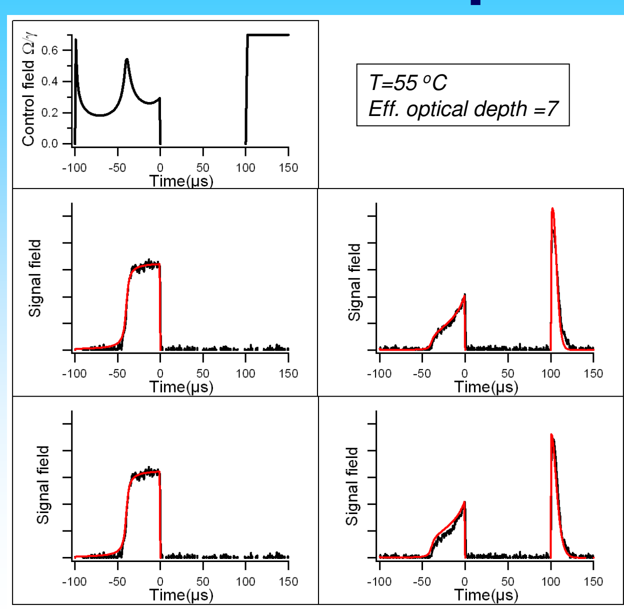
Simple 3-level system

Calculated efficiency – 0.39

With Doppler broadening and VCC

Calculated efficiency – 0.29

Control field optimization



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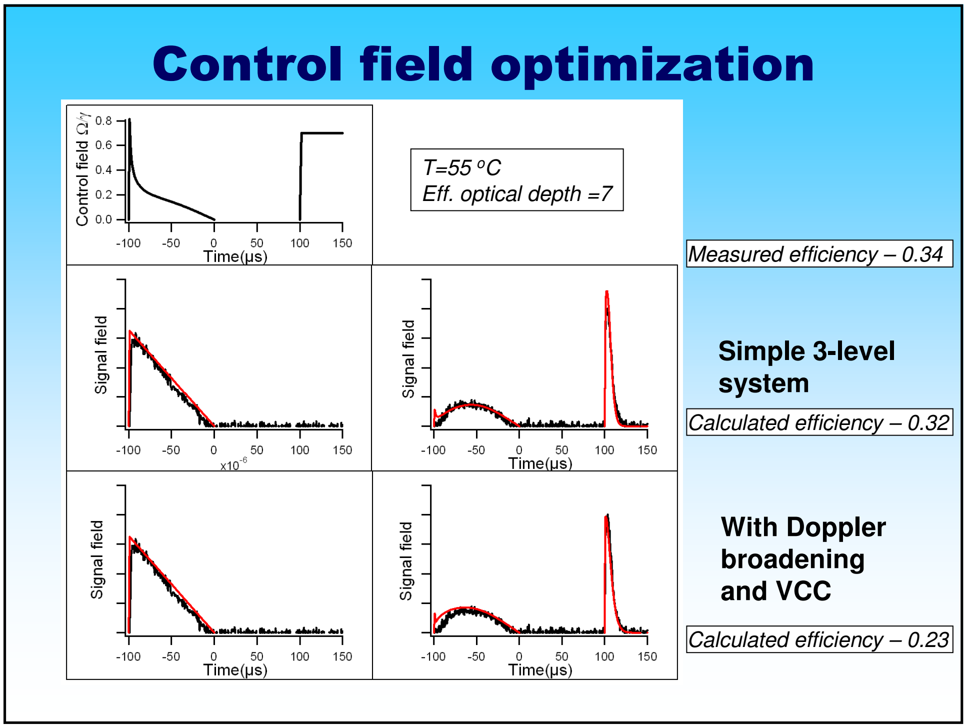
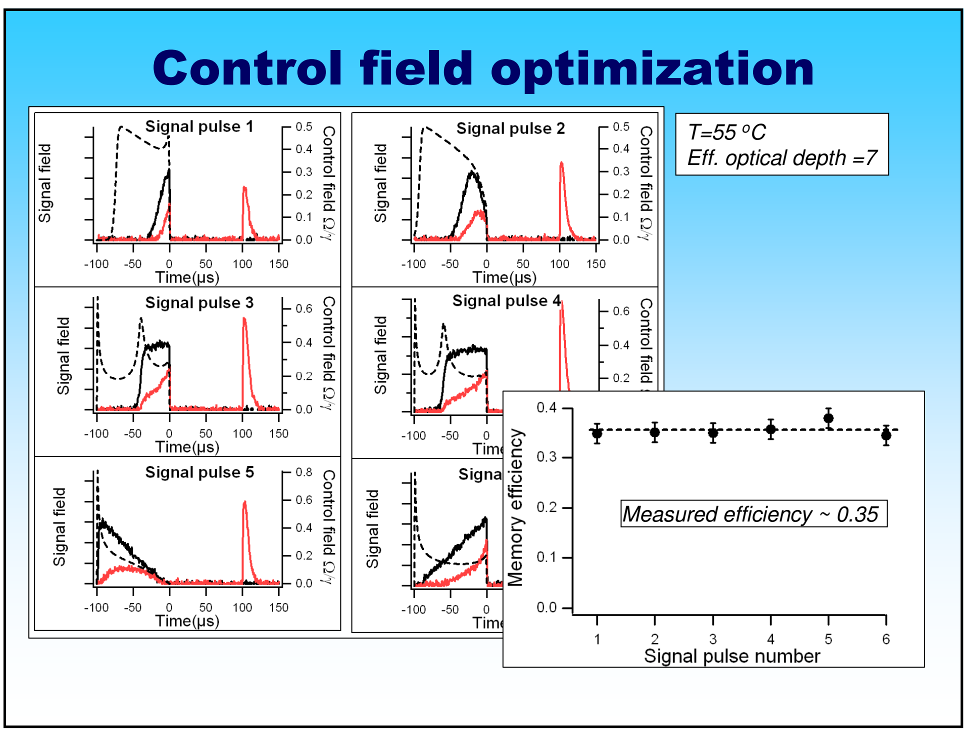


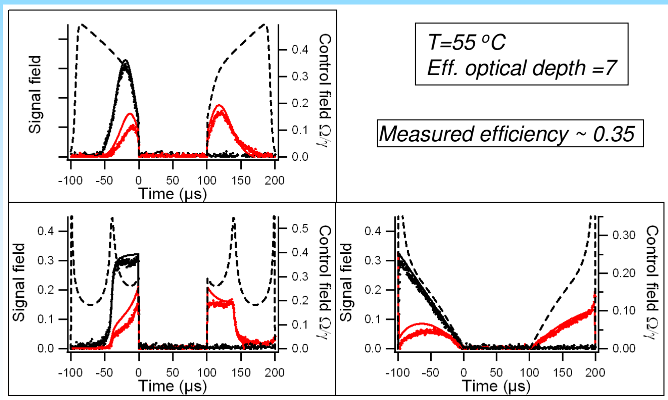
Control field optimization
T=55 °C
Eff. optical depth =7
Measured efficiency – 0.34
Simple 3-level system
Calculated efficiency – 0.32
With Doppler broadening and VCC
Calculated efficiency – 0.23
Control field Ω/γ
Signal field
Time(μs)



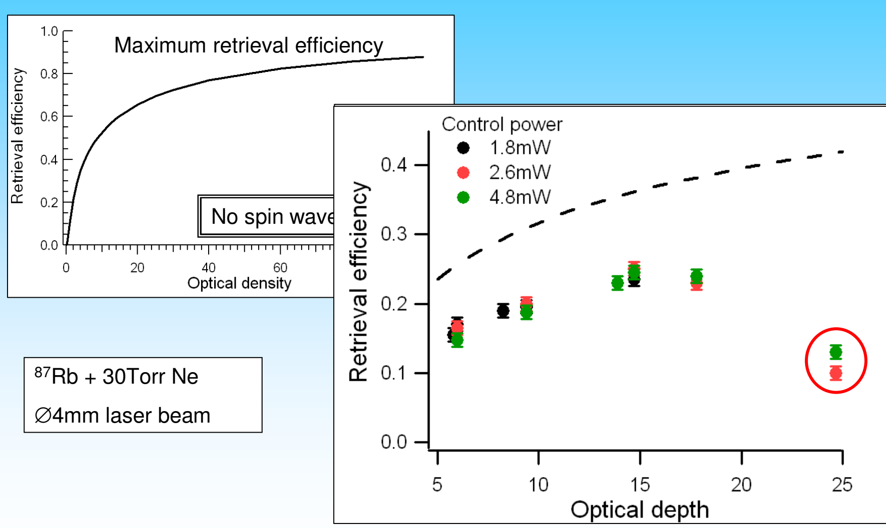
Control field optimization
T=55 °C
Eff. optical depth =7
Signal pulse 1
Signal pulse 2
Signal pulse 3
Signal pulse 4
Signal pulse 5
Signal field
Control field Ω/γ
Time(μs)
Measured efficiency ~ 0.35
Memory efficiency
Signal pulse number

Control field optimization

Storage with the calculated control field and retrieval with the same reversed control field reproduces original signal field pulse shaped (only reversed).



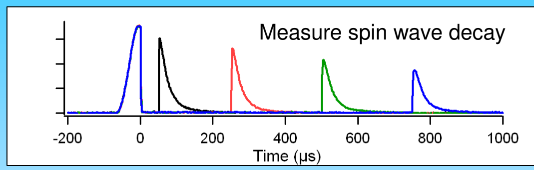
Temperature dependence

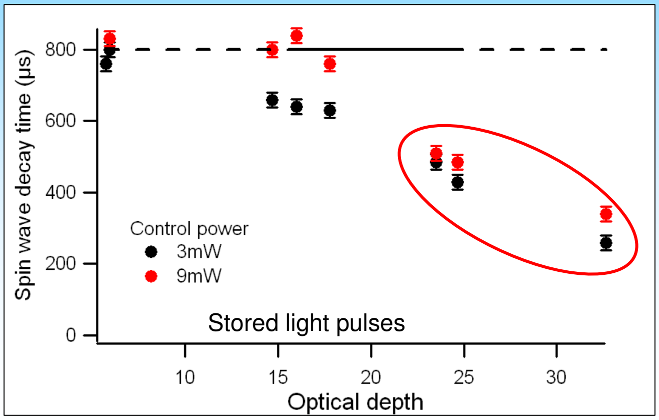


^{87}Rb + 30Torr Ne

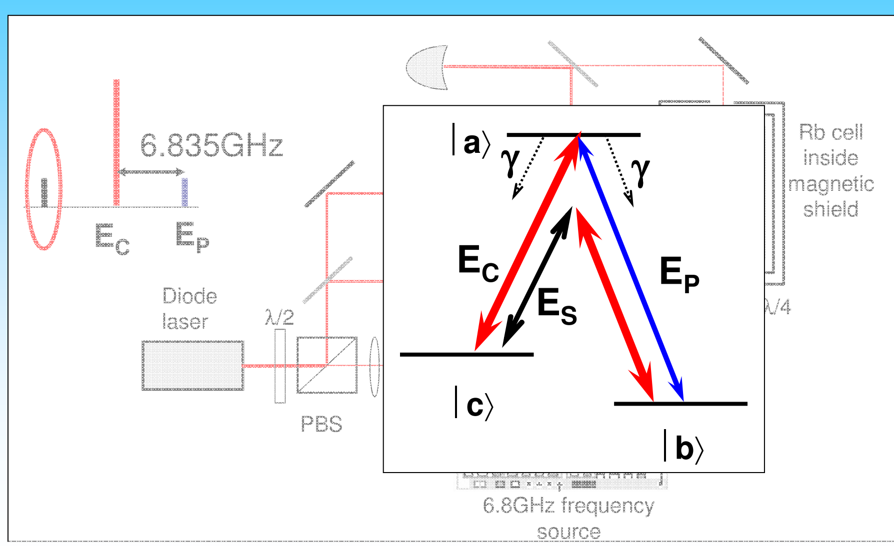
∅4mm laser beam

Temperature dependence

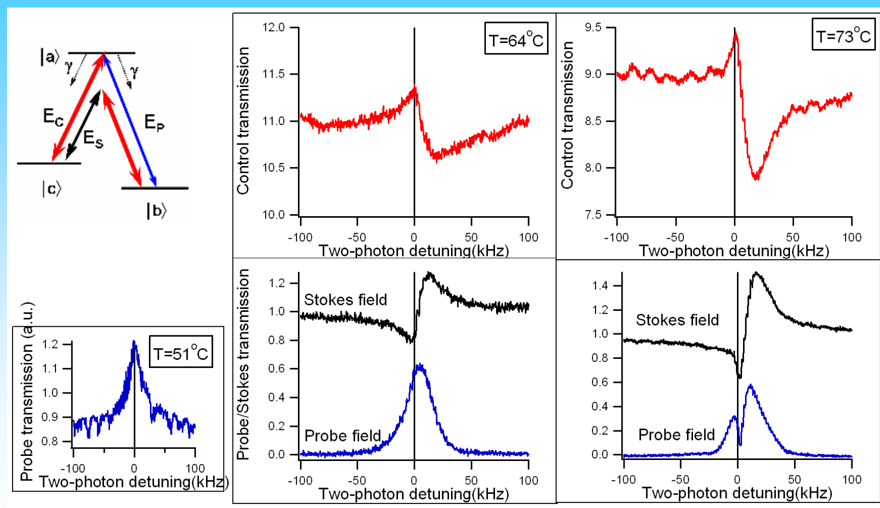




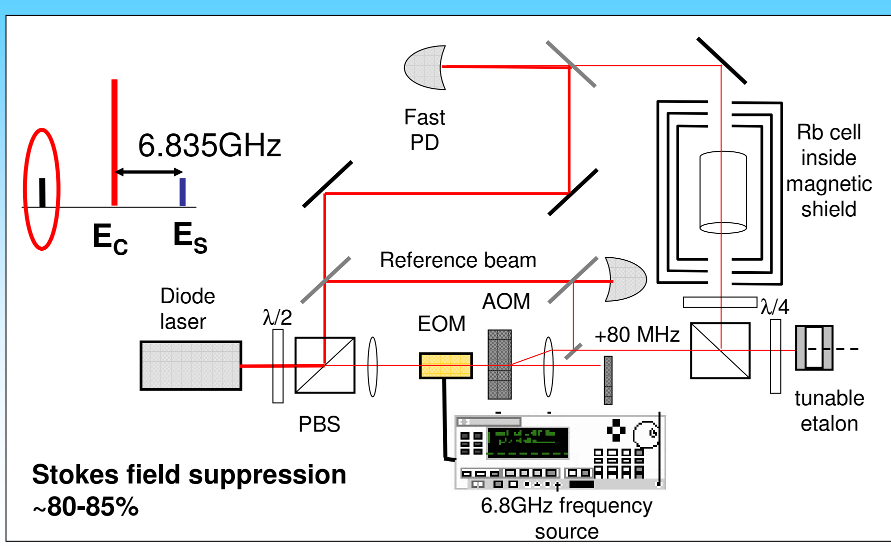
Four-wave mixing



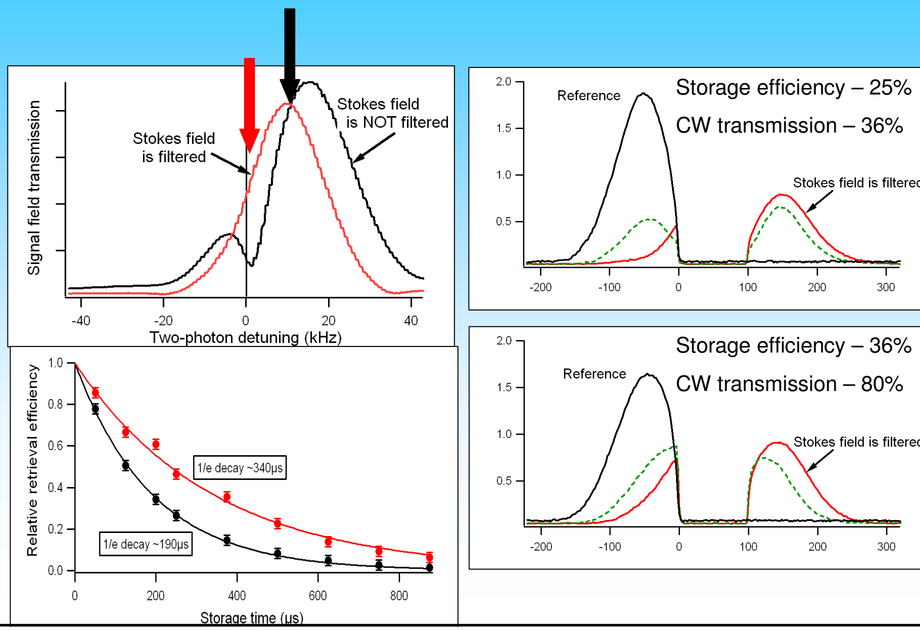
Four-wave mixing



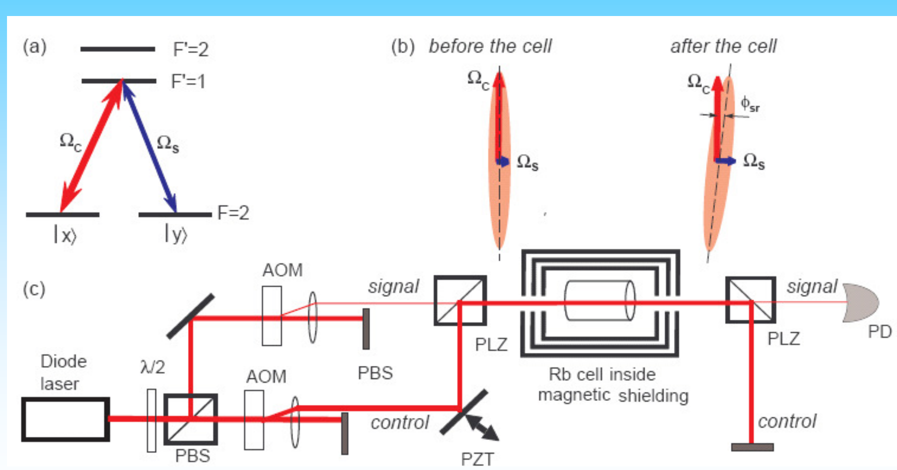
Four-wave mixing



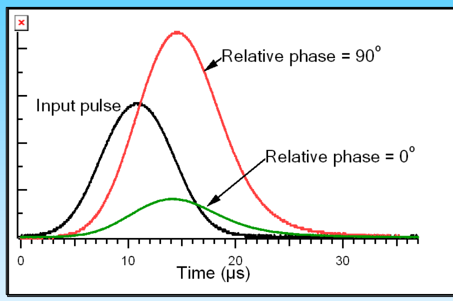
Four-wave mixing

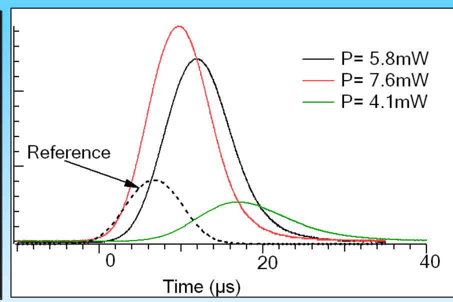


Slow light in an optical medium with integrated gain



Self-rotation induced "gain"

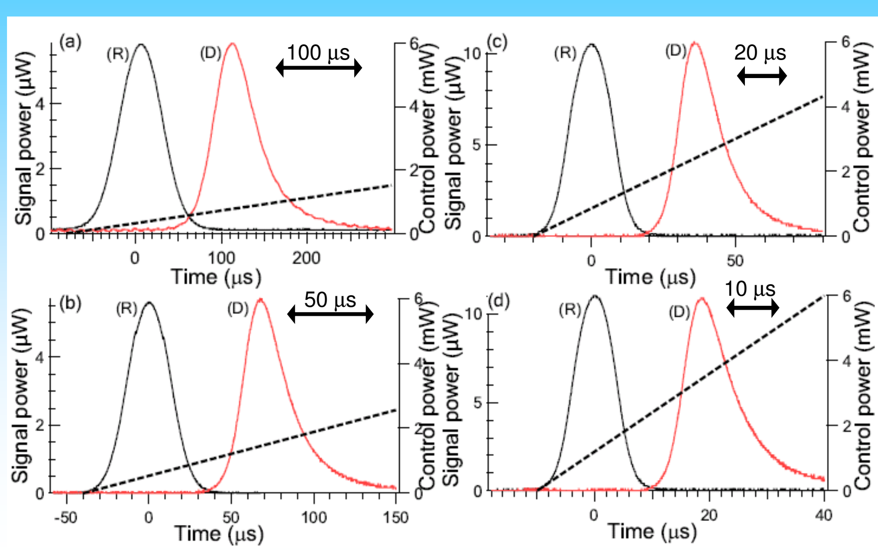




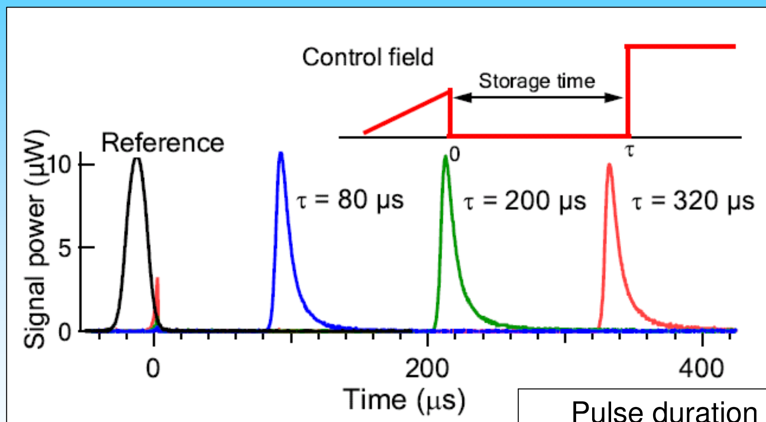
Relative phase b/w control and probe fields changes the amplitude of the transmitted probe pulse, but barely affect the pulse dynamics

As in "normal" slow light both group delay and pulse reshaping increases for a weaker control field

Slow light with a temporally varying group velocity



Stored light in the presence of self-rotation



Pulse duration =19ms

Fractional delay – up to 20

I. Novikova *et al.*, Phys. Rev. Lett. *in press* (2007); *e-print* 0706.3945 (2007).

Conclusions

- We've tested experimentally a stored light optimization algorithm based on time-reversal using weak classical pulses.
- Experimental results are in a good agreement with the theoretical predications.
- Changes in our experimental setup are required to avoid destructive effects of radiation trapping and four-wave mixing.

People

David F. Phillips
Cindy Hancox
Yanhong Xiao
Mason Klein
Michael Hohensee

Eugeniy Mikhailov
Nate Phillips
William Ames
Nathan Belcher
Trevor Harrison