Protocols for storage and read-out of atomic quantum memory for light

Jaromír Fiurášek

Department of Optics, Palacký University, 17. listopadu 50, 77200 Olomouc, Czech Republic

Collaborators:

Tomáš Opatrný
Nicolas Cerf
Eugene Polzik
Jacob Sherson
Brian Julsgaard
Arne Sorensen
Klaus Molmer

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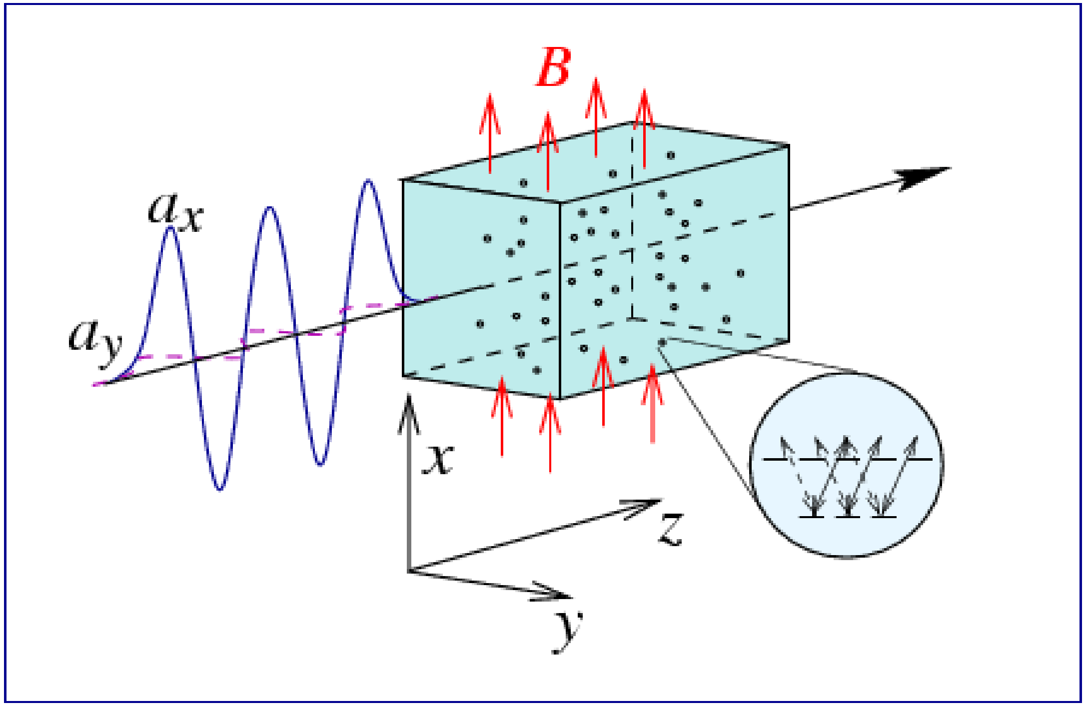
Outline of the talk

- **Off-resonant interaction of light with atomic ensemble**
- **Direct mapping of the quantum state of light onto atoms**
- **Cloning of coherent states of light onto atomic memory**
- **Readout protocol based on a simultaneous passage of two light beams through the atomic ensemble**
- **Readout protocol exploiting simultaneous passage of a single beam through the ensemble two perpendicular several directions**

Why do we need quantum memory ?

- **Quantum communication**
  - **Quantum memory is an essential component of quantum repeaters.**
  - **It is required for efficient entanglement distillation and purification**
- **Quantum computation**
  - **Quantum memory is necessary for scalable quantum computing with linear optics as proposed by KLM.**

Basic experimental configuration



Ensemble of 10^{12} Cs atoms held at a room temperature in a paraffin coated glass cell

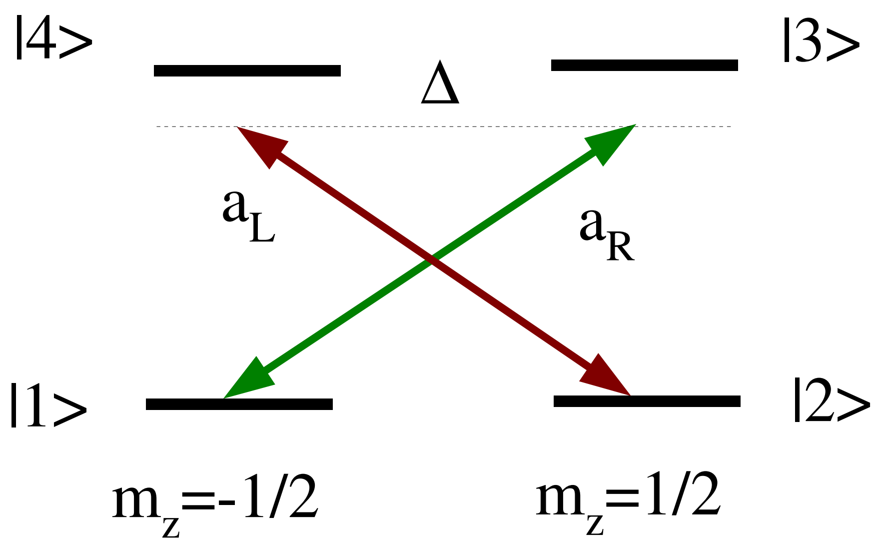
Atomic spins are initially oriented along the x axis

B – magnetic field

a_x — strong coherent linearly polarized coupling beam

a_y — quantum linearly polarized signal beam

Four level model



Interaction Hamiltonian after adiabatic ellimination of the excited states:

$$H = g\left(a_R^\dagger a_R |1\rangle\langle 1| + a_L^\dagger a_L |2\rangle\langle 2|\right)$$

AC-Stark shift of the atomic levels

Faraday effect – different ”refraction index” for R and L polarized beams

Collective atomic spin

defined as sum of the spin operators of all atoms

$$J_x = \frac{1}{2}\sum_j \left(|1\rangle_{jj}\langle 2| + |2\rangle_{jj}\langle 1|\right)$$

$$J_y = \frac{i}{2}\sum_j \left(|1\rangle_{jj}\langle 2| - |2\rangle_{jj}\langle 1|\right)$$

$$J_z = \frac{1}{2}\sum_j \left(|2\rangle_{jj}\langle 2| - |1\rangle_{jj}\langle 1|\right)$$

Commutation relations

$$[J_y, J_z] = i J_x$$

Optical pumping: $\langle J_x \rangle = \frac{1}{2} N_A$

We can replace J_x with $\langle J_x \rangle$

Quadrature operators of the effective atomic mode

$$x_A = \frac{J_y}{\langle J_x \rangle^{1/2}} \qquad p_A = \frac{J_z}{\langle J_x \rangle^{1/2}} \qquad [x_A, p_A] = i$$

Stokes vector describing polarization of the light beam

$$S_x = \frac{1}{2}(a_R a_L^\dagger + a_R^\dagger a_L)$$

$$S_y = \frac{i}{2}(a_R a_L^\dagger - a_R^\dagger a_L)$$

$$S_z = \frac{1}{2}(a_R a_R^\dagger - a_L^\dagger a_L)$$

Commutation relations

$$[S_y, S_z] = i S_x$$

Strong x polarized beam: $\langle S_x \rangle = \frac{1}{2} N_L$

We can replace S_x with $\langle S_x \rangle$

Quadrature operators of the y-polarized light mode:

$$x_L = \frac{S_y}{\langle S_x \rangle^{1/2}} \qquad p_L = \frac{S_z}{\langle S_x \rangle^{1/2}} \qquad [x_L, p_L] = i$$

Quantum non-demolition coupling

Total Hamiltonian $$H_{tot} = g \sum_j (a_R^\dagger a_R |1\rangle_{jj}\langle 1| + a_L^\dagger a_L |2\rangle_{jj}\langle 2|)$$

$$H_{tot} = \frac{1}{2} g (N_A N_L + 4 S_z J_z)$$

The term $N_L N_A$ is a constant of motion and can be dropped

Resulting Hamiltonian expressed in terms of quadrature operators:

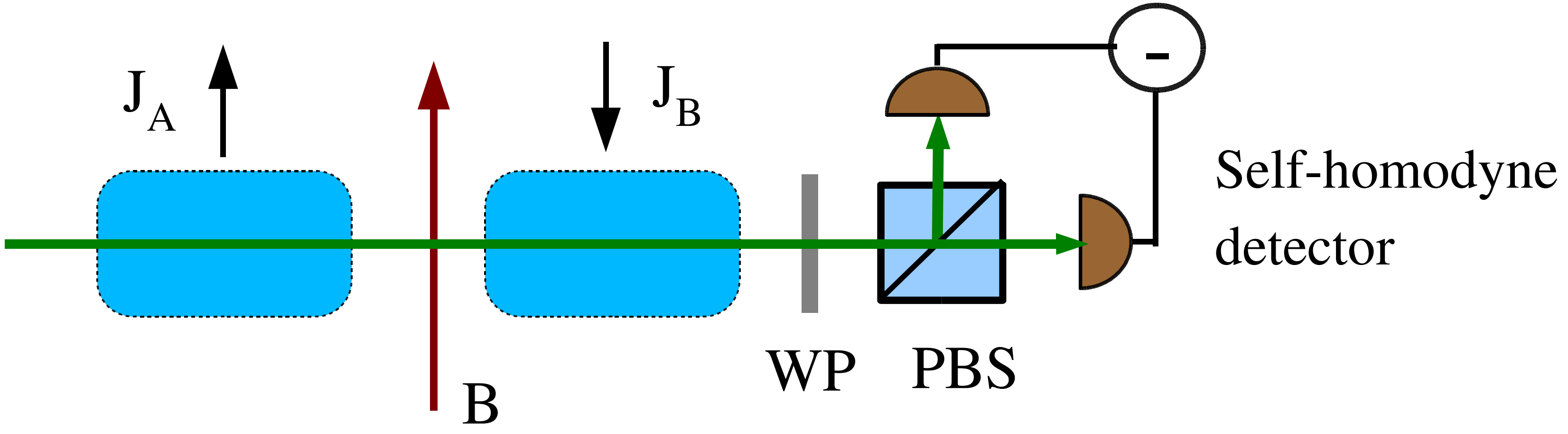
$$H_{eff} = \kappa p_L p_A$$

Collective enhancement of the interaction strength: $\kappa = g\sqrt{N_A N_L}$

Basic quantum memory unit

Light is detected on Ω sidebands in order to suppress the technical noise present at low frequencies. This modifies the dynamics of the system.

Use two cells with oppositely polarized spins as a memory unit!



The QND interaction is recovered, a non-local atomic mode couples to the cos(Ωt) mode of the light beam.

Limitations of the system

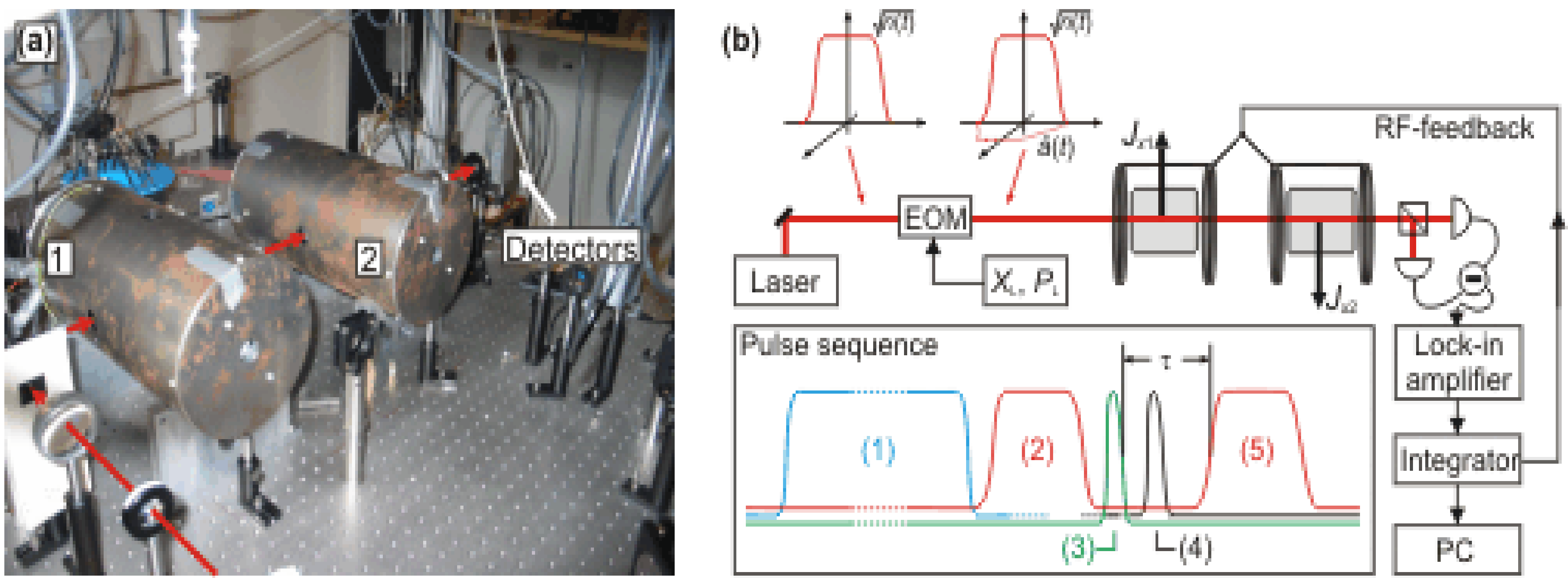
Large detuning of the light beam is required in order to suppress absorption and resulting decoherence.

Sufficiently strong coupling strength is achieved by using long puses whose duration is typically T=1 ms. The condition TΩ>>1 must be satisified.

This rules out protocols involving several sequential passages of the light beam through the ensemble since a long pulse would have to be stored somewhere between the passages.

It is necessary to devise protocols involving only a single passage of the beam through the atoms.

Quantum memory for light



B. Julsgaard, J. Sherson, J.I. Cirac, J.F., and E.S. Polzik, *Nature (London)* **432**, 482 (2004).

Direct mapping of the quantum state of light onto atoms

1. **Light beam passes through the atomic memory unit, κ=1:**

$$x_{L,out} = x_L + p_A \qquad x_{A,out} = x_A + p_L$$

$$p_{L,out} = p_L \qquad p_{A,out} = p_A$$

2. **The x quadrature of the output light beam is measured, we get** $x_{L,meas}$

3. The p quadrature of atomic mode is displaced by $-x_{L,meas}$

Atomic quadratures after the direct mapping:

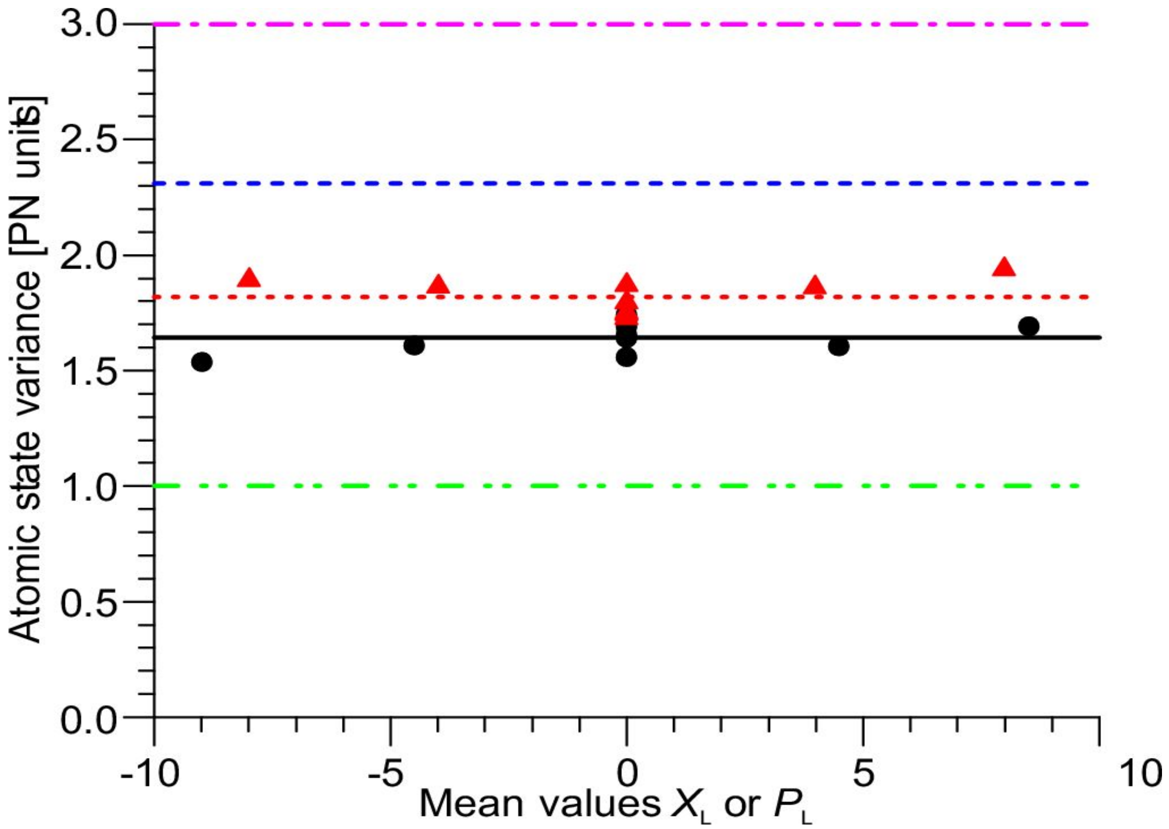
$$x_{A,out} = x_A + p_L$$

$$p_{A,out} = -x_L$$

Perfect mapping achieved in the limit of infinitely squeezed x_A

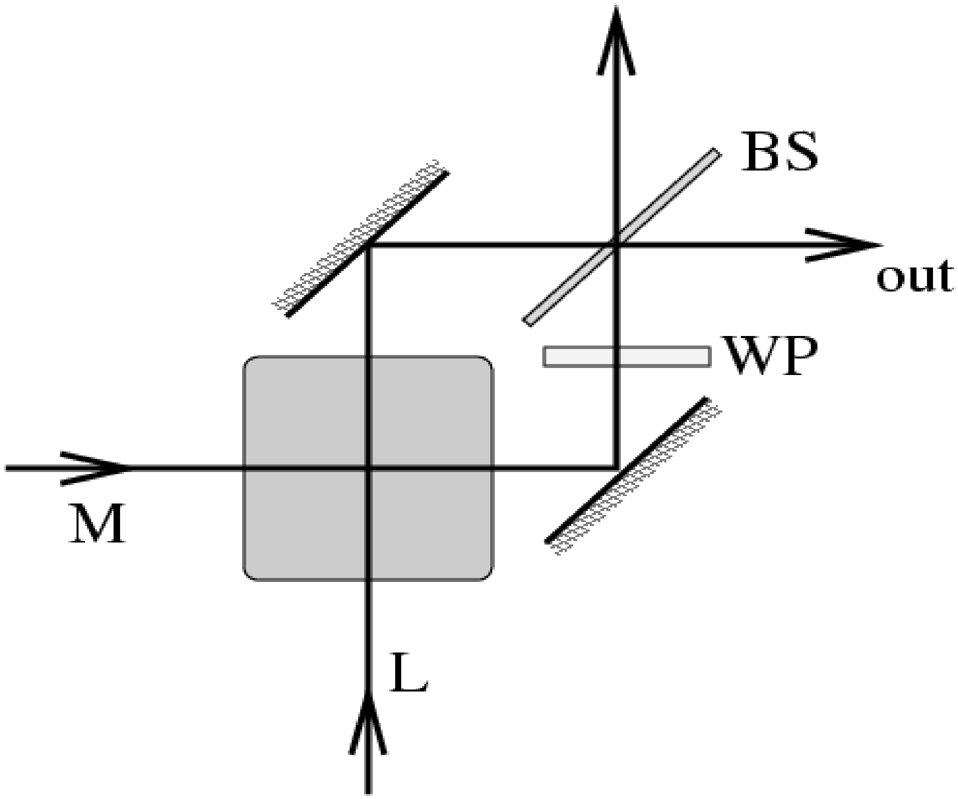
Experimental results

Experimental transfer gains: **g_x=0.80, g_p=0.84**



Fidelity of storage of coherent state |α> with |α|²<8: F_{exp}=66.7% F_{class}=55.4%

Single passage readout of the atomic memory



- **Two light beams L and M cross the atomic ensemble simultaneously in perpendicular directions**
- The beam L reads the atomic quadrature x_A and the beam M retrieves the quadrature p_A

J.F., J. Sherson, T. Opatrny, and E.S. Polzik, quant-ph/0510099.

Input-output transformations

Simultaneous passage of two beams changes dynamics of the system

Light modes with non-constant temporal profile $f'(t)=\sqrt{\frac{3}{T}}(1-\frac{2t}{T})$ are coupled to the modes with constant profile $f(t)=\sqrt{1/T}$

Unity gain readout is achieved for $\kappa=2^{1/2}$.

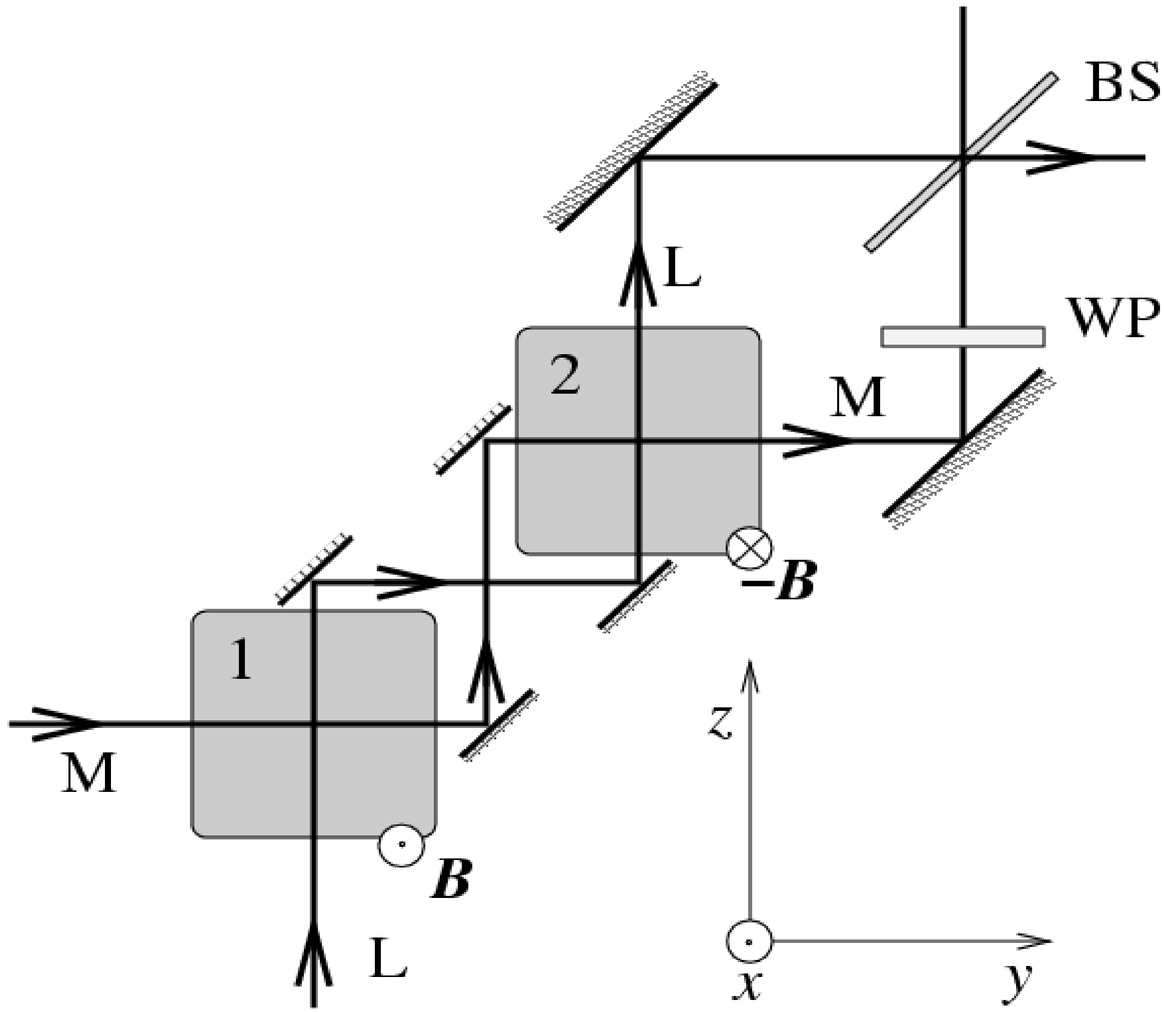
$$x_{L,out}=p_A+\frac{1}{\sqrt{2}}x_L-\frac{1}{\sqrt{6}}p'_M \qquad x_{A,out}=x_A+\sqrt{2}\,p_L$$

$$p_{L,out}=-x_A-\frac{1}{\sqrt{2}}x_M-\frac{1}{\sqrt{6}}p'_L \qquad p_{A,out}=p_A+\sqrt{2}\,p_M$$

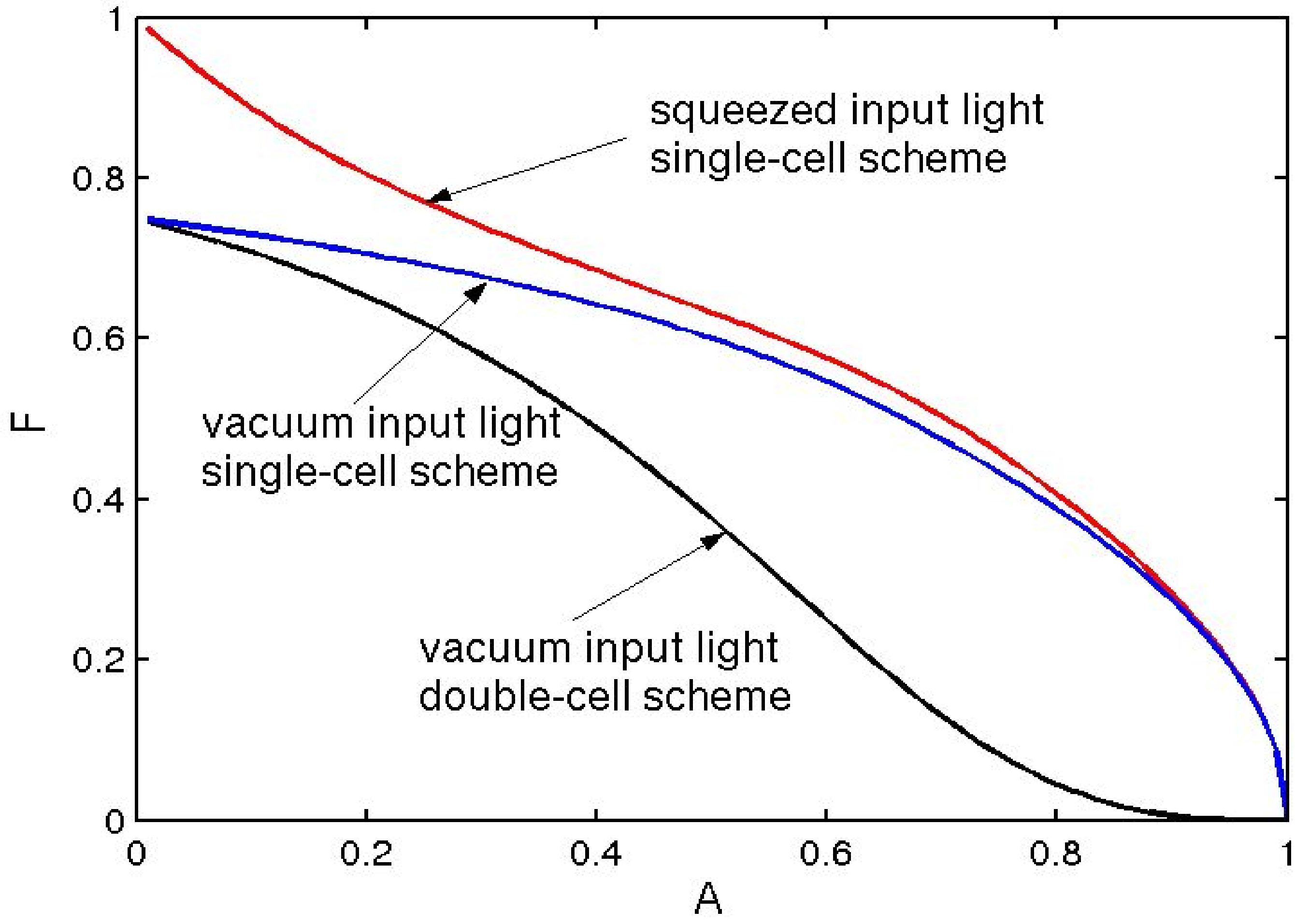
The readout is imperfect due to noise stemming form the input light quadratures.

Fidelity of retrieval of coherent state F=75%

Readout of atomic memory consisting of two ensembles

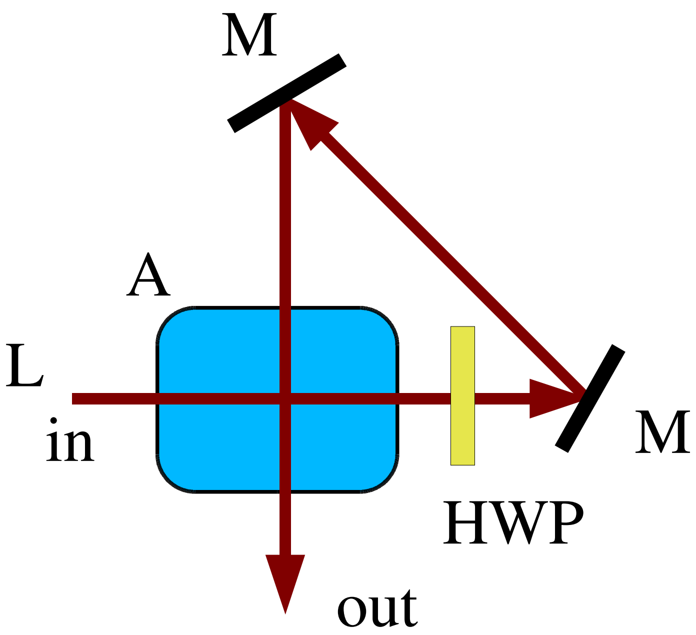


Fidelity of the readout of coherent states



Fidelity is reduced due to losses of light on the walls of the glass cells holding the atoms.

Readout using single long pulse



First passage: $H=\kappa p_A p_L$

Second passage: $H=\kappa x_A x_L$

The long light pulse passes simultaneously through the atomic ensemble in two perpendicular directions.

J. Sherson, A. S. Soerensen, J.F., K. Moelmer, and E. Polzik, quant-ph/0505170.

Dynamics of the system

$$x_A(t) = x_A(0) + \int_0^t dt' \kappa(t') P_L(t')$$

$$p_A(t) = p_A(0) \mathrm{e}^{-\int_0^t dt' \kappa^2(t')} - \int_0^t dt' \kappa(t') e^{-\int_{t'}^t du \kappa^2(u)} X_L(t')$$

$$X_{L,out}(t) = X_L(t) + \kappa(t) p_A(t)$$

$$P_{L,out}(t) = P_L(t) - \kappa(t) x_A(t)$$

$X_L(t)$ and $P_L(t)$ denote quadrature operators of a light pulse segment at time t.

$$[X_L(t), P_L(t')] = i\delta(t - t')$$

$$x_L = \frac{1}{\sqrt{T}} \int_0^T X_L(t) dt \qquad p_L = \frac{1}{\sqrt{T}} \int_0^T P_L(t) dt$$

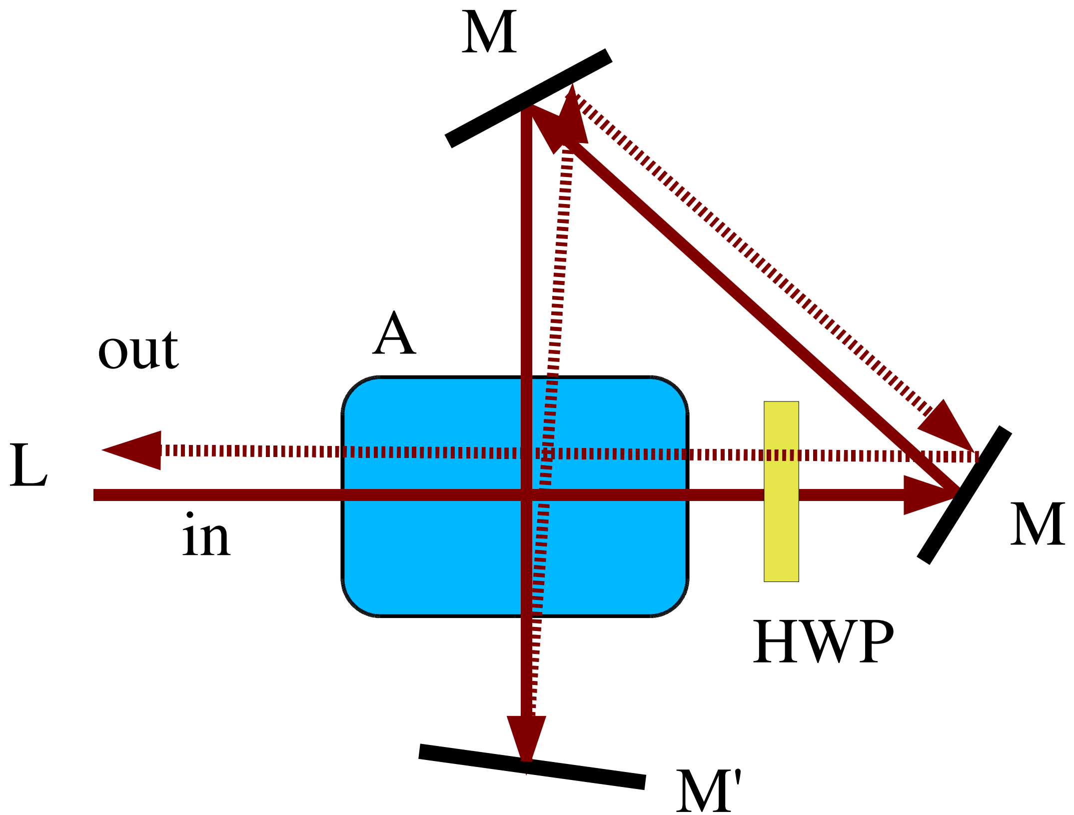
Retrieval of the state stored in a memory

Coupling strength κ(t) can be made time dependent by using x-polarized coupling beam with the temporal intensity profile $|\kappa(t)|^2$.

$$\kappa(t)=\sqrt{\frac{1}{2(T-t)}} \qquad x_{L,out}=\frac{1}{2}x_L+\frac{1}{\sqrt{2}}p_A \qquad p_{L,out}=-\sqrt{2}\,x_A$$

- **The atomic quadrature x_A is perfectly transferred onto light**
- **The readout of the quadrature p_A is imperfect**
- **The noise can be suppressed by initially squeezing x_L**
- **The protocol is asymmetric**
- **κ(t) diverges, needs to be truncated in practice**

Symmetric readout protocol



After the first two passages the light beam is reflected back and again passes twice through the atomic ensemble.

Dynamics of the system

Most conveniently expressed in terms of annihilation operators:

$$a_A(t) = a_A(0)\mathrm{e}^{-2\int_0^t dt'\kappa^2(t')} - 2i\int_0^t dt'\kappa(t')e^{-2\int_{t'}^t du\,\kappa^2(u)} A_L(t')$$

$$A_{L,out}(t) = A_L(t) - 2i\kappa(t)a_A(t)$$

Effectively a beam-splitter type mixing between atomic and optical mode.

Temporal profile f(t) of the mode which couples to atoms can be controlled by choosing κ(t) according to:

$$\frac{1}{\kappa(t)}\frac{d\kappa(t)}{dt} + 2\kappa^2(t) = \frac{1}{f(t)}\frac{df(t)}{dt}$$

Storage and retrieval

Perfect storage is achieved for: $\kappa(t) = \frac{1}{2\sqrt{t}}$

Perfect retrieval is achieved for: $\kappa(t) = \frac{1}{2\sqrt{T-t}}$

κ(t) has to be truncated to finite value in practice.

Total coupling strength: $\kappa_{tot}^2 = \int_0^T \kappa^2(t)\,dt$

Fidelity of the storage/retrieval protocol: $F \approx 1 - \exp(-\kappa_{tot}^2/2)$

Conclusions

- **Quantum memory is an essential component of quantum repeaters.**
- **Quantum memory is also necessary for scalable quantum computing with linear optics as proposed by KLM.**
- **Atomic ensembles allow to implement quantum memory for light.**
- **Storage of weak coherent states into memory was experimentally demonstrated.**
- **Feasible protocols for transfer of the state stored in the memory back onto light were proposed.**