Transients of the quantum light retrieved from Rydberg polaritons

@QuantumPSA

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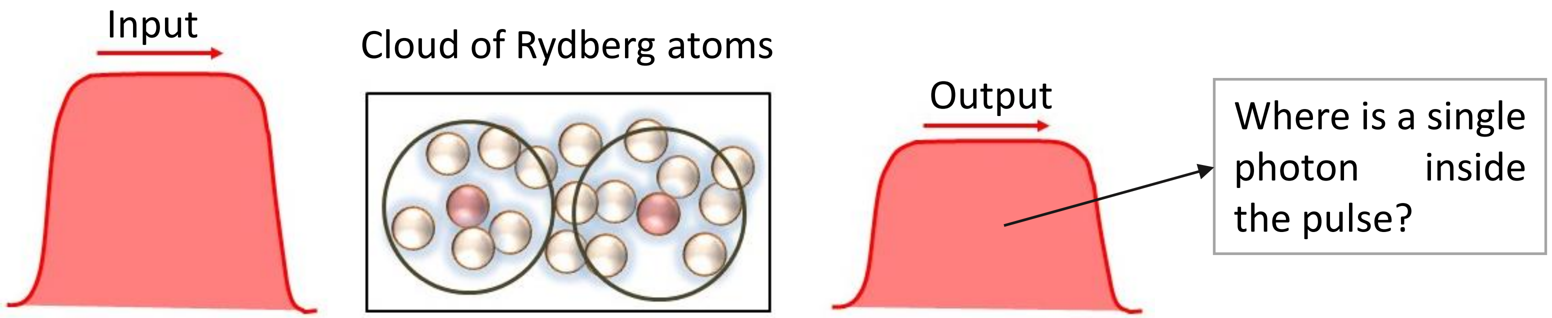
1. INTRODUCTION

- In quantum communications, the generation of narrowband **single photons on demand** is a key ingredient [1].

In this work, we study the transients of light pulses propagating through an ensemble of **Rydberg atoms** under **electromagnetically induced transparency** and study how to exploit them to generate single photons on demand.

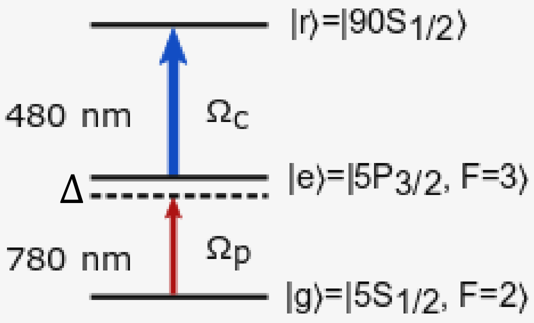
Basic question:

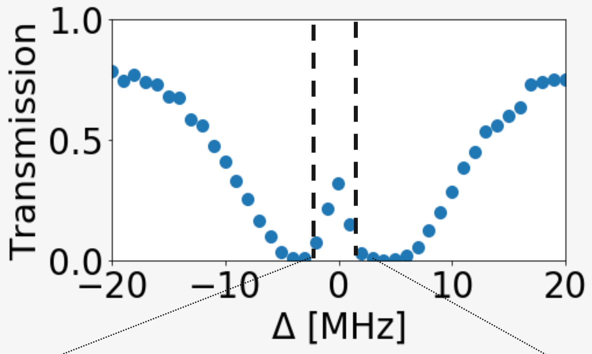


Where is a single photon inside the pulse?

2. BACKGROUND

A) We excite ^{87}Rb atoms to a Rydberg state with $\boldsymbol{n = 90}$ under conditions of **electromagnetically induced transparency (EIT)** [2]

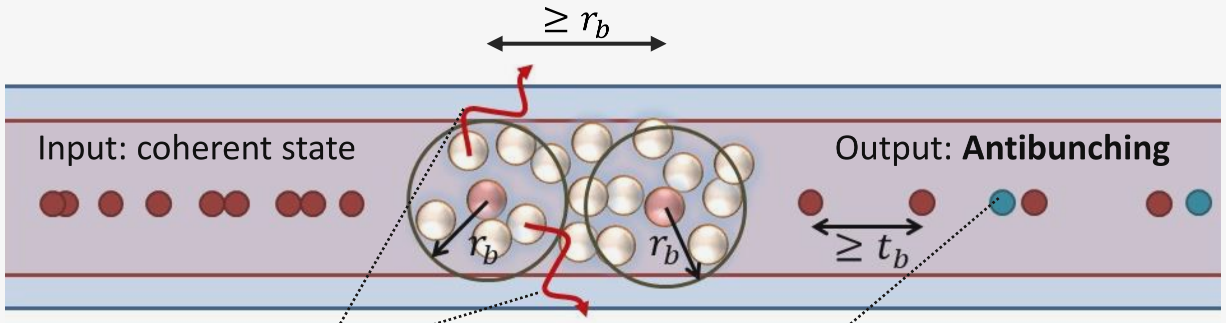




B) The cloud is transparent to probe photons.

C) Within the transparency window, photons propagate as **Rydberg polaritons**, with a group velocity $\boldsymbol{v_{gr} \ll c}$ [2]

D) Rydberg blockade: Strong interactions between Rydberg atoms prevent the formation of two polaritons closer than the **blockade radius** $\boldsymbol{r_b}$ [3]



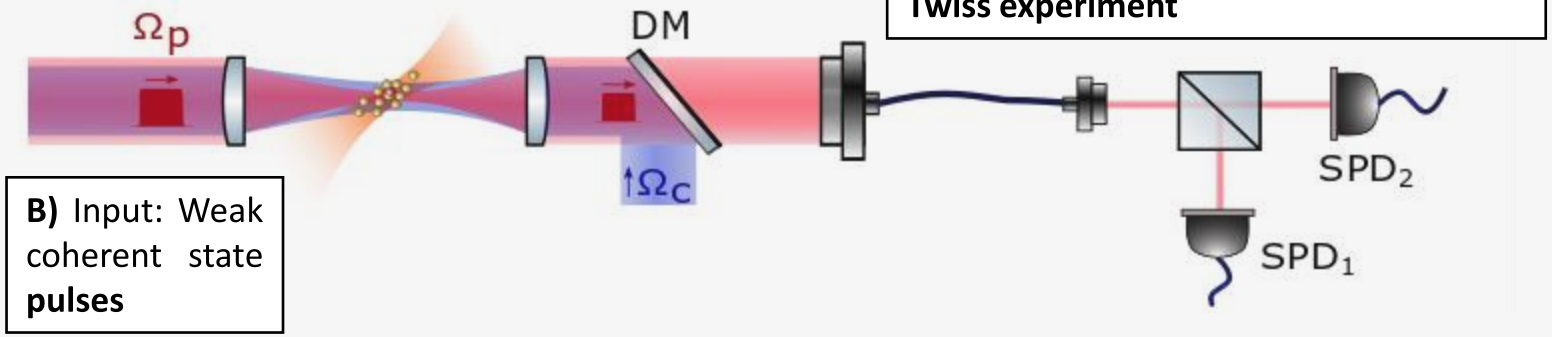
E) Extra photons inside a blockade radius are (ideally) scattered away

F) Output photons have a minimum separation between them.

G) The presence of non-scattered photons at the output depends on the **optical depth per blockade radius** $\boldsymbol{OD_b}$ [4]

3. METHODS

A) Atoms loaded in a dipole trap. Only few Rydberg excitations can exist inside the medium at a time due to Rydberg blockade



B) Input: Weak coherent state **pulses**

C) Statistics of the output light (second-order correlation function $\boldsymbol{g^{(2)}}$) is measured with a **Hanbury-Brown and Twiss experiment**

Second-order correlation function:

$$g^{(2)}_{\Delta t}(t,\tau) = \frac{P_c(\Delta t)}{P_1(\Delta t)P_2(\Delta t)}$$

- $P_c(\Delta t)$ is the probability to have a coincidence
- $P_1(\Delta t)$ is the probability to have a click in SPD$_1$
- $P_2(\Delta t)$ is the probability to have a click in SPD$_2$
- t is the arriving time at SPD$_1$
- $t + \tau$ is the arriving time at SPD$_2$
- Δt is the time window where looking for clicks

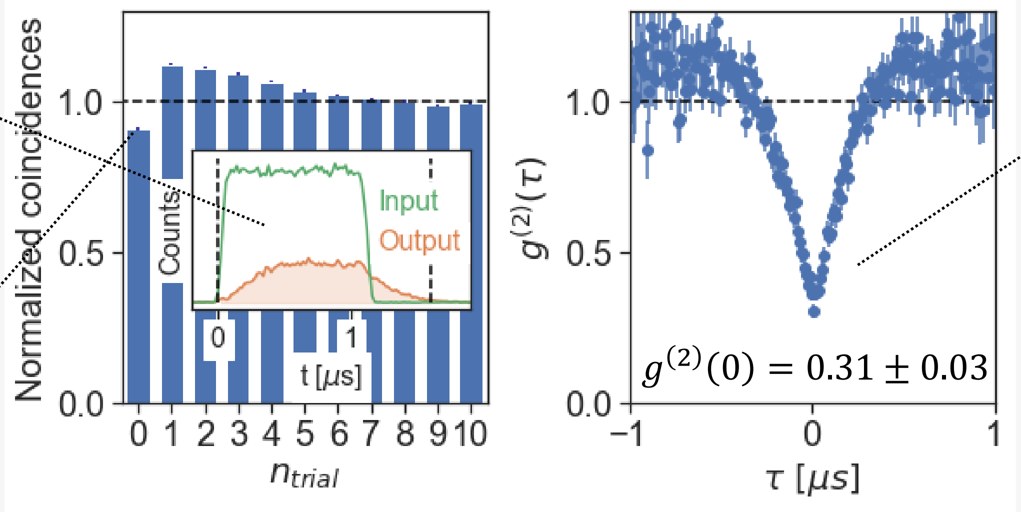
4. RESULTS

4.1 Statistics of the full output pulse

A) Temporal distribution of input and output pulses

B) The statistics of the entire output pulse are

- **Quantum**: $g^{(2)} = 0.908 \pm 0.004$
- Far from the single photon ($g^{(2)} < 0.5$).



C) "Common" **Rydberg EIT antibunching** [4]: Only one photon leaves the medium at a time, delocalized within the output pulse

D) Basic question: Can we find a single photon localized somewhere throughout the pulse?

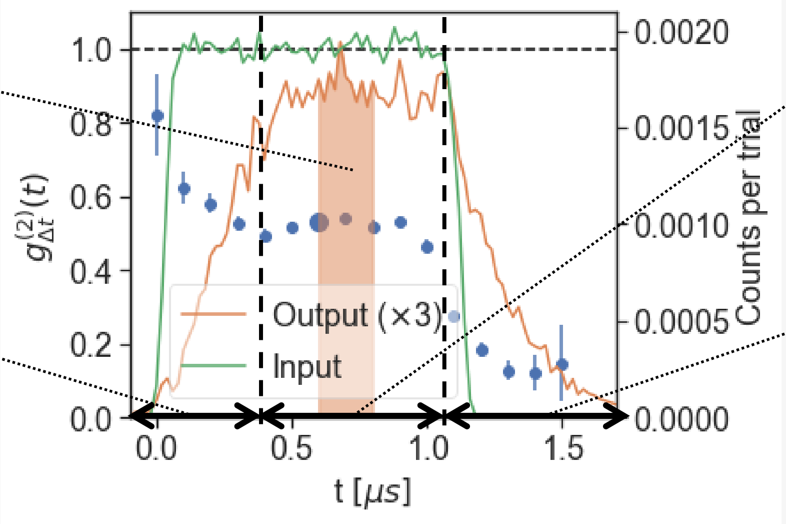
4. RESULTS

4.2 Study of the transients

A) Time window of starting time t and duration $\Delta t = 200$ ns moving along the pulse

B) First transient: Input field is switched on.

- $g^{(2)}_{\Delta t}(t)$ higher tan in the steady state
- It lasts approximately the time it takes for a polariton to cross the medium ($\propto v_{gr}^{-1}$) [5]



C) Steady state regime:

- $g^{(2)}_{\Delta t}(t)$ depends on OD_b

D) Second transient: Input field is switched off.

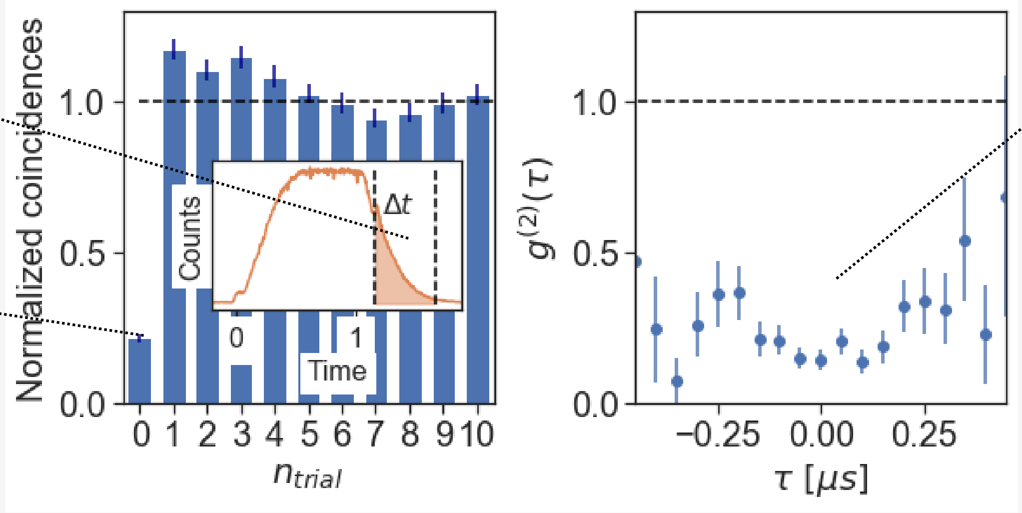
- $\boldsymbol{g^{(2)}_{\Delta t}(t)}$ **smaller than in the steady state**
- It lasts approximately the time it takes for a polariton to cross the medium [5]
- Similar to photons retrieved after storage

4.3 Generation of single photons from the second transient

A) We only take **the last $\boldsymbol{\Delta t = 500}$ ns** of the output pulse

B) The statistics of the total 500 ns window:

- **Single photon**: $g^{(2)} = 0.218 \pm 0.015$



C) $g^{(2)}(\tau)$ low along the 500 ns window

D) Answer: We have a single photon localized at the end of the pulse

4. RESULTS

4.3 Generation of single photons from the second transient

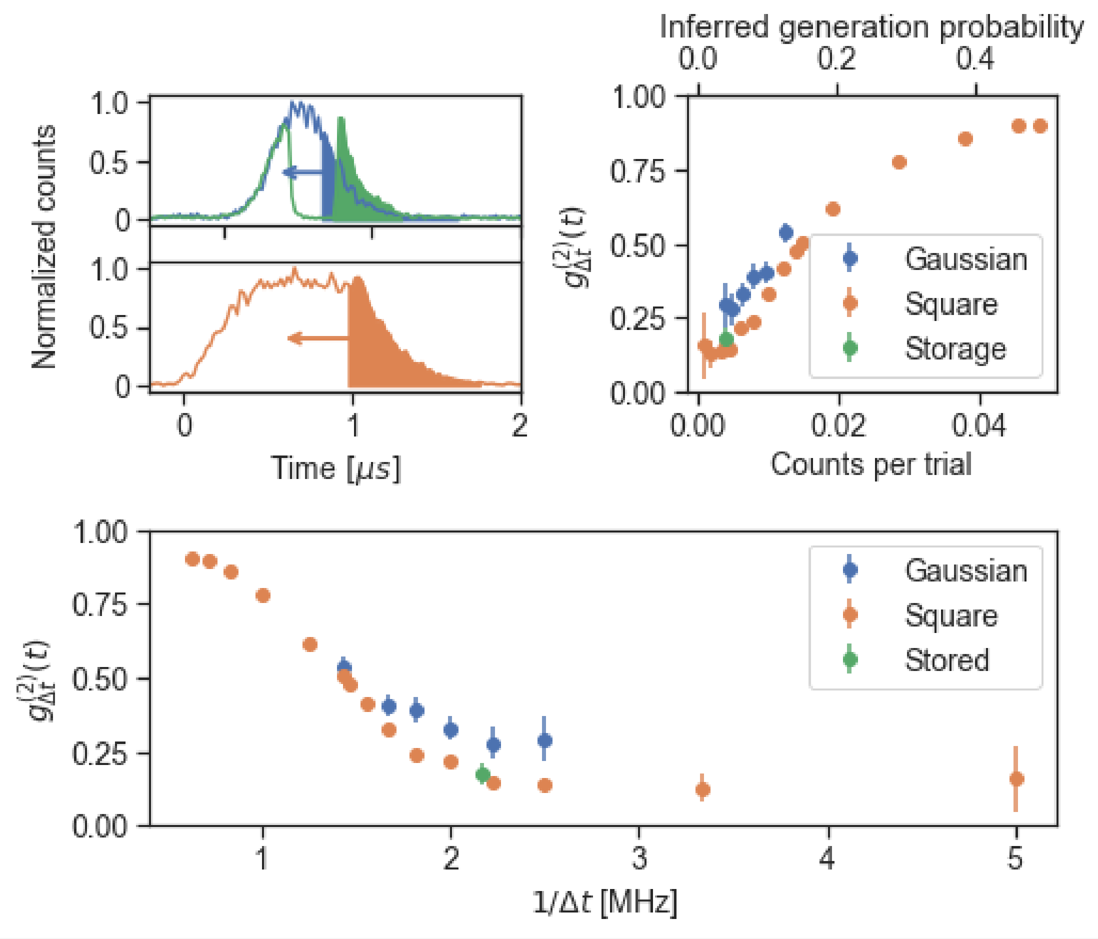
A) Comparison of the transmitted squared pulse with stored and transmitted gaussian pulse

B) In general: when Δt increases:

- Larger generation probability
- Worse $g^{(2)}_{\Delta t}(t)$
- Smaller bandwidth

C) Square VS Gaussian: It is better to switch on and off faster.

D) Square VS Storage: Generation probability similar or lower when storage for the same $g^{(2)}_{\Delta t}(t)$



4. CONCLUSIONS

1. We studied the propagation of weak coherent state pulses in a cold atomic ensemble in the regime of Rydberg EIT.
2. We found that the $g^{(2)}_{\Delta t}$ depends on the position along the pulse and it strongly decreases at the end.
3. We demonstrated that it can be used to generate single photons on demand (localized within a pulse).

5. REFERENCES

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[6] Similar work: Möhl, Charles, et al. "Photon correlation transients in a weakly blockaded Rydberg ensemble." *Journal of Physics B: Atomic, Molecular and Optical Physics* 53.8 (2020): 084005.

6. ACKNOWLEGMENTS

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