Routing of Optical States by Atomic Media

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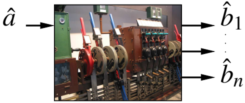
Introduction

Routing of Optical States by Atomic Media

Problem:



- Non-linear upconversion in crystals (Tanzilli et al. Nature **437** (2005))
  → low conversion efficiency
- Storage in atomic vapor, retrieval on second transition (Zibrov et al. PRL **88** (2002))
  → Losses due to storage
- Four wave mixing
  → created fields are absorbed

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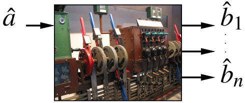

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Our Approach:

- Transfer the optical fields adiabatically (similar to STIRAP)
- Avoid absorption using electromagnetically induced transparency

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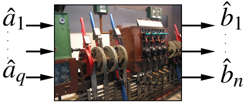

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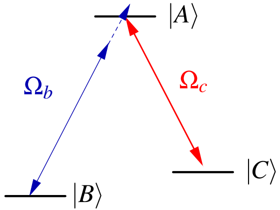
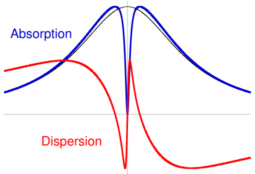
- Transfer the optical fields adiabatically (similar to STIRAP)
- Avoid absorption using electromagnetically induced transparency
- Framework for multiple input modes

Electromagnetically Induced Transparency: Slow Light





EIT is a quantum interference effect.
Atomic medium with Λ-like level configuration

Ω_c control field

Ω_b (weak) signal field

$$\hat{H}_{\text{int}} = \hbar\,\Omega_b\,|A\rangle\langle B| + \hbar\,\Omega_c\,|A\rangle\langle C| \quad + \text{h.a.}$$

$$|\text{Dark state}\rangle \propto \quad \Omega_c\,|B\rangle - \Omega_b\,|C\rangle$$

- Excitation processes $|C\rangle \rightarrow |A\rangle$ and $|B\rangle \rightarrow |A\rangle$ interfere destructively.
- No absorption on two-photon resonance.
- Sensitive phase dependence.
- Strong dispersion $\frac{dn}{d\omega}$:

$\Rightarrow$ Reduction of group velocity $v_g = \frac{c}{n+\omega\frac{dn}{d\omega}}$

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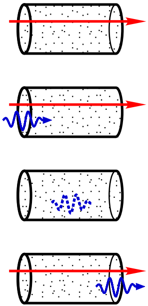
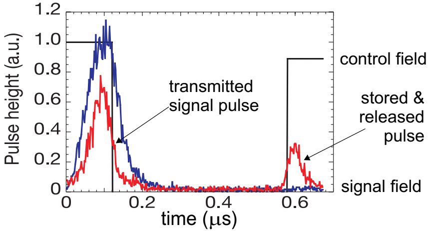
Electromagnetically Induced Transparency: Stopping of Light



Stopping of light

- Turn on control laser:
  medium gets transparent for signal mode
- Signal enters the medium:
  pulse is slowed down, compressed spatially
- Control is turned off adiabatically:
  group velocity reduces to zero,
  pulse is stored in a collective ground state superposition.
- Control is turned on adiabatically: signal pulse is restored.



Reproduced from T. Chanelière et. al., Nature 438 (2006)

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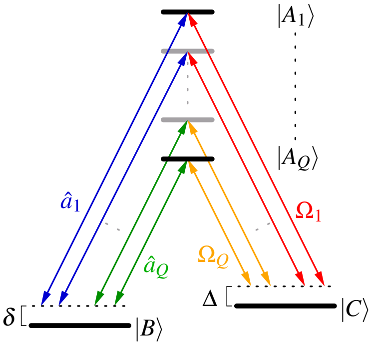
EIT in Multi-Λ Systems PRA 73, 013804 (2006)

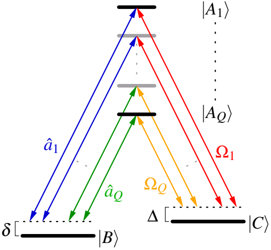


Λ-system with multiple excited levels

- Ω_q strong ⇒ Classical control fields
- $\hat{a}_q$ weak quantized signal field modes
- δ, Δ small detunings
  ⇒ each field couples one transition
- Dicke limit: signals' coupling strengths g_q identical for all atoms

- How to handle EIT in this system?
- Which signal mode will propagate?

Multi-Λ system



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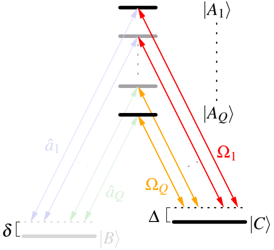
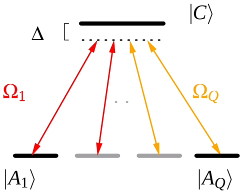


Interaction Hamiltonian
(neglecting weak fields $\hat{a}_q$):

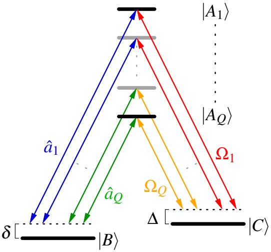
$$\hat{H}^{(0)}_{\text{int}} = -\hbar\Delta - \hbar\sum_q \Omega_q\,|A_q\rangle\langle C| + \text{H.a.}$$



$Q-1$ excited 'dark states' $|ED_r\rangle$

one excited 'bright state' $|EB\rangle$

Multi-Λ system



Only one superposition of the excited states

$$|EB\rangle = \sum \frac{\Omega_q}{\Omega} |A_q\rangle$$

couples to $|C\rangle$.

$$\Omega = \sqrt{\sum |\Omega_q|^2}$$

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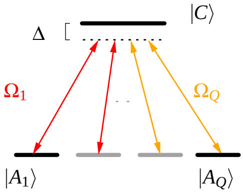

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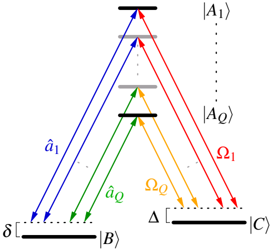

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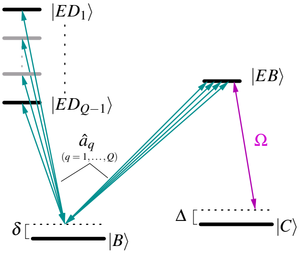
Change of the atomic basis: $\{|A_q\rangle\} \rightarrow \{|EB\rangle, |ED_r\rangle\}$



Quantum fields $\hat{a}_q$ couple to all $|ED_r\rangle$ → Absorption

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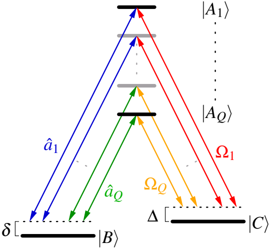

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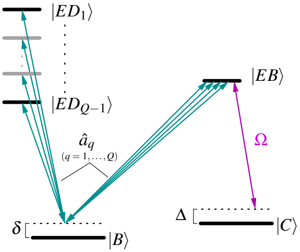


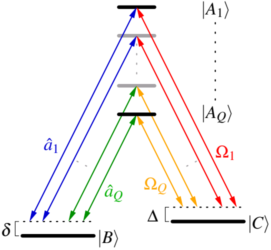
Quantum fields $\hat{a}_q$ couple to all $|ED_r\rangle \to$ Absorption

Only one superposition couples only to $|EB\rangle$:

$$\hat{b}_Q = \frac{1}{R} \sum \frac{\Omega_q^*}{g_q^*} \hat{a}_q.$$

$$R = \sqrt{\sum |\Omega_q / g_q|^2}$$

Multi-Λ system



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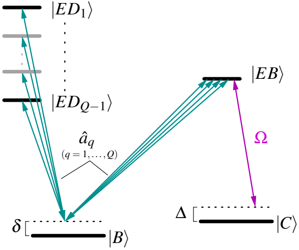

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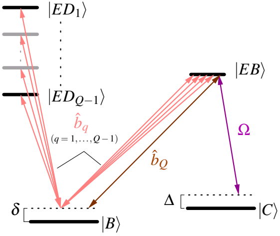
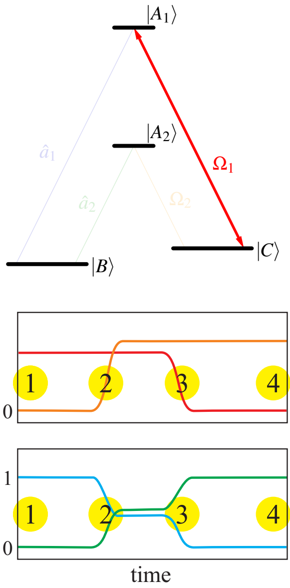
Change of the optical basis: $\{\hat{a}_q\} \rightarrow \{\hat{b}_q\}$



Reduction to single-Λ system:

- One mode $\hat{b}_Q$ experiences EIT
- The other modes are absorbed

Raman Adiabatic Transfer of Optical States



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1. Switch on control field Ω_1
   EIT-mode $\hat{b}_2(\Omega_1, \Omega_2) = \hat{a}_1$.

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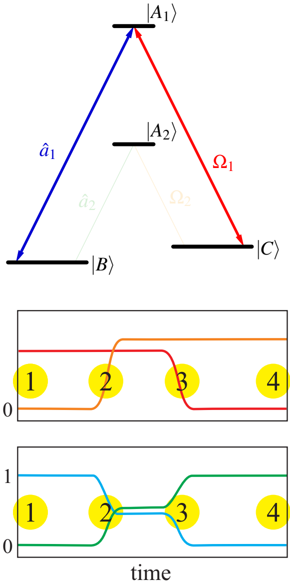

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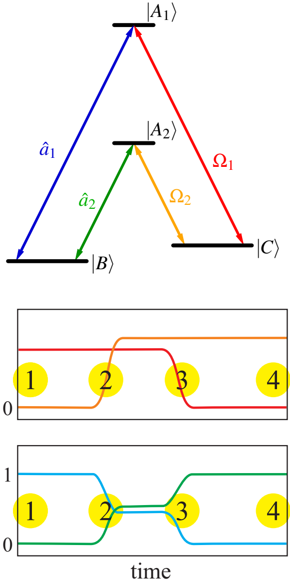

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2. Slowly switch on control field Ω_2
   signal follows into the new EIT-Mode adiabatically

$$\hat{b}_2(\Omega_1, \Omega_2) \rightarrow \frac{1}{R}\left(\frac{\Omega_1^*}{g_1^*}\hat{a}_1 + \frac{\Omega_2^*}{g_2^*}\hat{a}_2\right)$$

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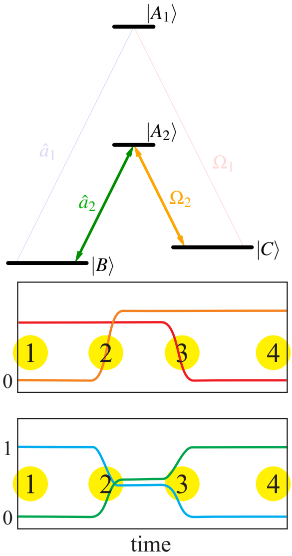

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3. Switch off control field Ω_1:
   EIT-mode $\hat{b}_2(\Omega_1, \Omega_2) \to \hat{a}_2$.

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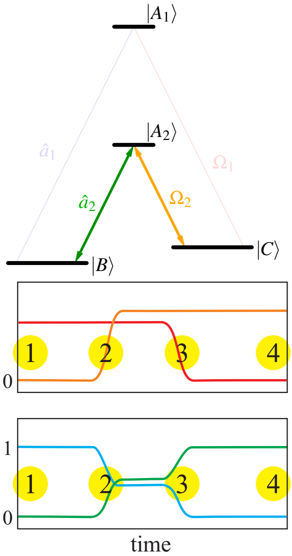

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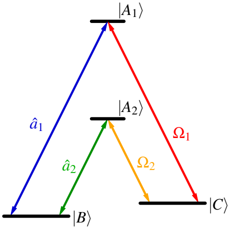
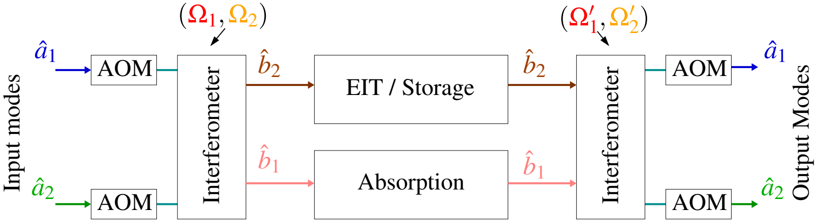
4. The original signal has been converted from mode $\hat{a}_1$ to mode $\hat{a}_2$ ⇒ STIRAP for optical modes

Adiabatic control allows routing

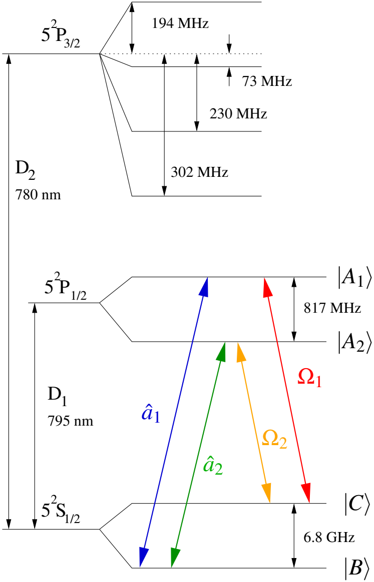


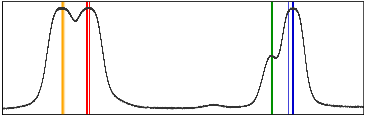
is equivalent to

- One superpostion of input modes is selected: $\hat{b}_2(\Omega_1, \Omega_2)$.
- This mode experiences EIT; orthogonal modes get absorbed.
- Phase and amplitudes of the input- and output modes are controlled by the control fields Ω_1, Ω_2.
- Equivalent to a linear optics circuit



The Physical System





- Atomic Medium: ^{87}Rb
- 50 mm long cell, 5 torr Neon as buffer gas, cell magnetically shielded, 60° C

$\hat{a}_1$	Ti:Sapphire laser
$\hat{a}_2$	generated mode; detection via heterodyning to Ti:Sapphire
Ω_1	Diode laser, phase locked to Ti:Sapphire $\hat{a}_1$ at 6.8 GHz
Ω_2	Diode laser, phase locked to Ω_1 at 817 MHz

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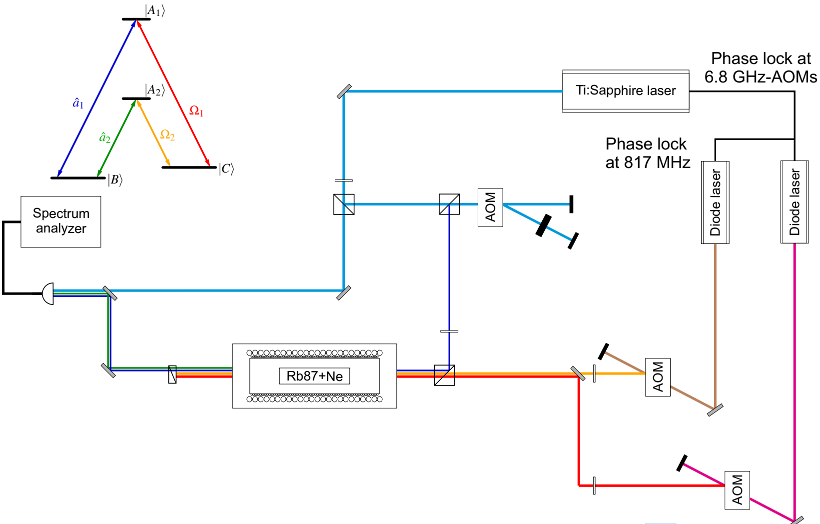
The Setup



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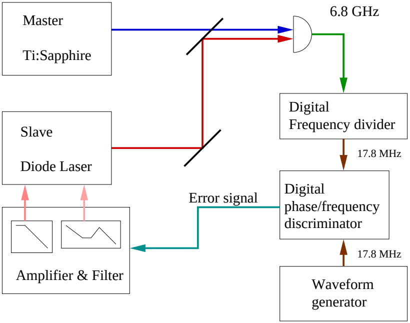
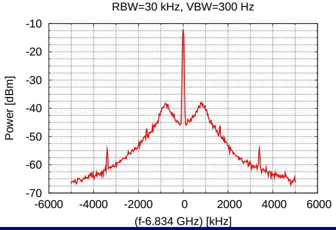
Laser Phase Lock



Properties

- using mobile communication ICs
- loop bandwidth >1 MHz
- large capture range
- scan, sweep, modulation control
- very versatile



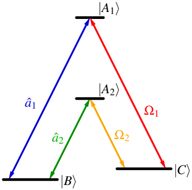
The Experiment

Experimental procedure:

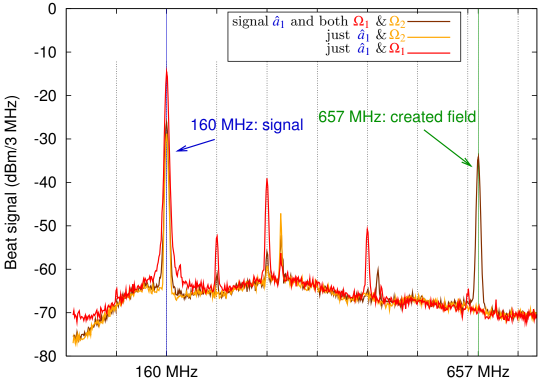
- Mode match all the beams for maximum beat signal
- Create four-wave-mixing: Shine in both control lasers and the signal

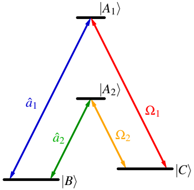
  $$\rightarrow \omega_{\text{signal}_2} = \omega_{\text{signal}_1} - (\omega_{\text{pump}_1} - \omega_{\text{pump}_2})$$

  is created.
- Store light pulses
- Retrieve stored pulses with second pump laser
- Observe RATOS



Four-wave mixing





160 MHz

Beat note between signal and Ti:Sa

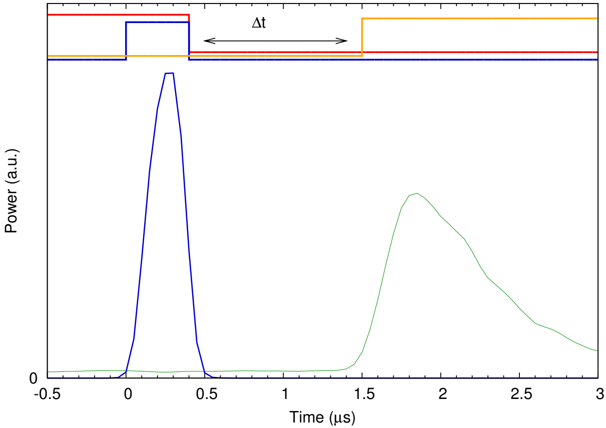
657 MHz

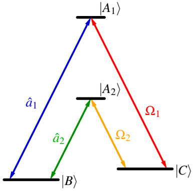
Beat note between created field and Ti:Sa

⇒ Mode matching is sufficient for the creation and detection of the new field

Storage of light

Storage and retrieval of a 400 ns pulse.





- Creation of ground state coherence
- Transfer efficiency $> 80\%$ compared to retrieval on same frequency.

⇒ Frequency conversion is possible if the pulse is stored

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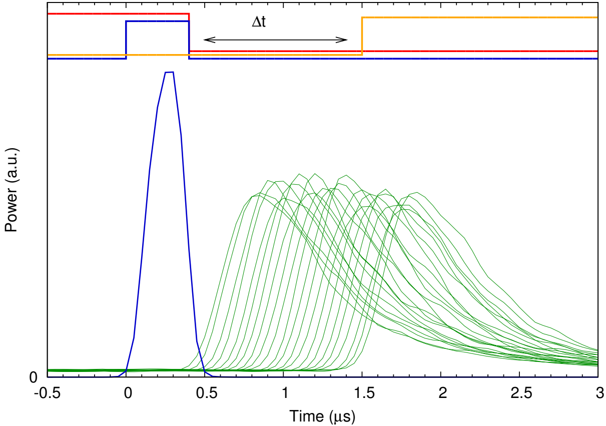
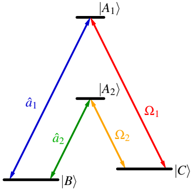
Storage of light

Storage and retrieval of a 400 ns pulse.



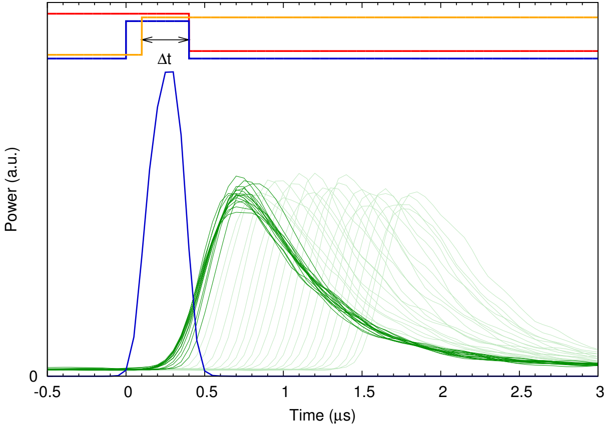


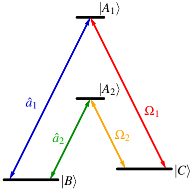
- Decoherence time $\approx 100\mu s$.
- Decoherence due to transit broadening

$\Rightarrow$ Frequency conversion is possible if the pulse is stored

Adiabatic transfer

Adiabatic transfer of a 400 ns pulse.





Adiabatic process

- Efficiency independent of overlap

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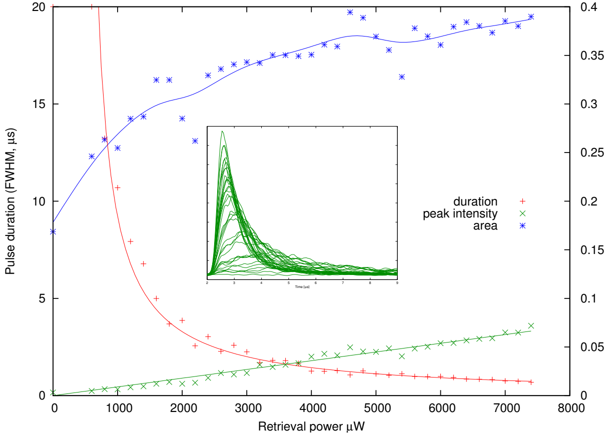

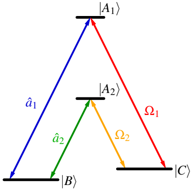

Adiabatic process

- Efficiency independent of overlap
- Efficiency independent of power

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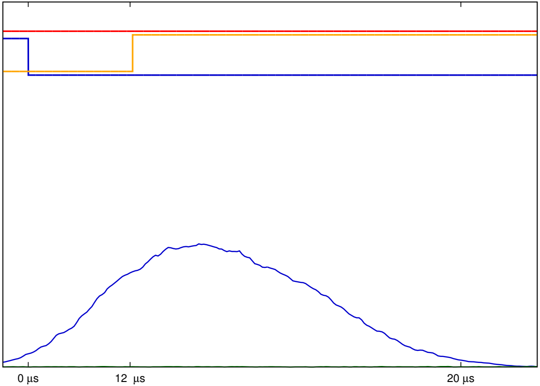
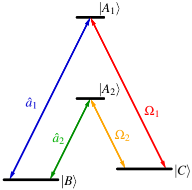
Beam Splitting

Control Powers: $\Omega_1 \triangleq 2.8\,\mathrm{mW}, \Omega_2 \triangleq 0\,\mathrm{mW}$





- Simultaneous retrieval with both control lasers splits the pulse into different frequency modes
- splitting ratio defined by $\frac{\Omega_1}{\Omega_2}$

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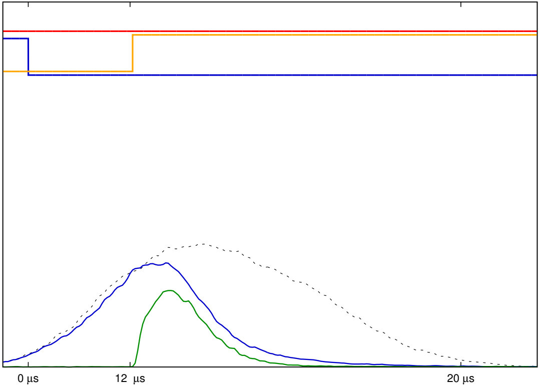
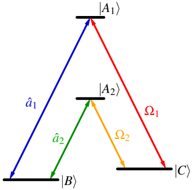
Beam Splitting

Control Powers: $\Omega_1 \triangleq 2.8\,\mathrm{mW}, \Omega_2 \triangleq 2.8\,\mathrm{mW}$

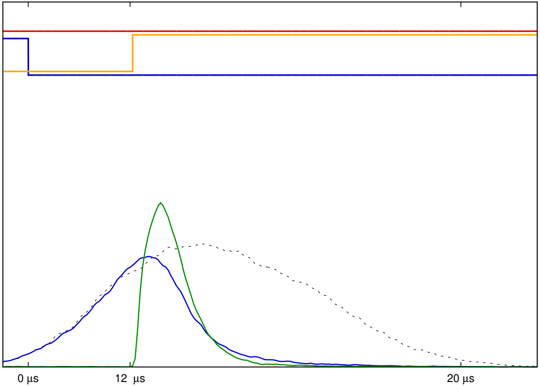


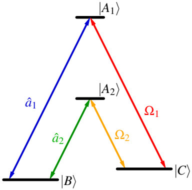


- Simultaneous retrieval with both control lasers splits the pulse into different frequency modes
- splitting ratio defined by $\frac{\Omega_1}{\Omega_2}$

Beam Splitting

Control Powers: $\Omega_1 \hat{=} 2.8\,\text{mW}, \Omega_2 \hat{=} 3.9\,\text{mW}$

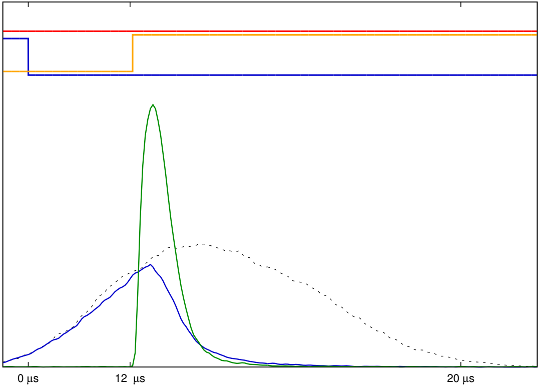


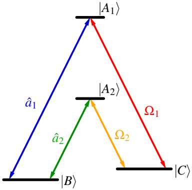


- Simultaneous retrieval with both control lasers splits the pulse into different frequency modes
- splitting ratio defined by $\frac{\Omega_1}{\Omega_2}$

Beam Splitting

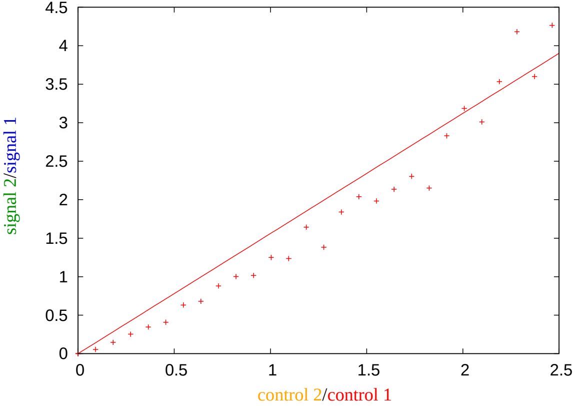
Control Powers: $\Omega_1 \triangleq 2.8\,\mathrm{mW}, \Omega_2 \triangleq 6.5\,\mathrm{mW}$

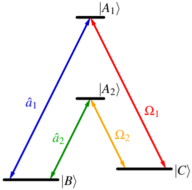




- Simultaneous retrieval with both control lasers splits the pulse into different frequency modes
- splitting ratio defined by $\frac{\Omega_1}{\Omega_2}$

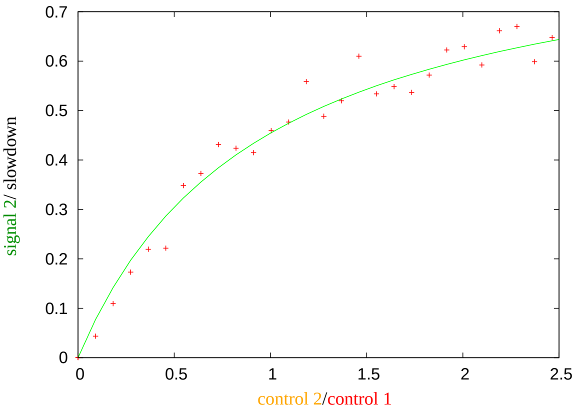
Beam Splitting

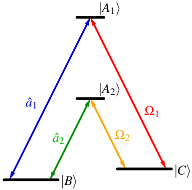




- Simultaneous retrieval with both control lasers splits the pulse into different frequency modes
- splitting ratio defined by $\frac{\Omega_1}{\Omega_2}$

Beam Splitting





- Simultaneous retrieval with both control lasers splits the pulse into different frequency modes
- splitting ratio defined by $\frac{\Omega_1}{\Omega_2}$

Conclusion

- **R**aman **A**diabatic **T**ransfer of **O**ptical **S**tates
    - Theory for an arbitrary number of upper levels
      $\Rightarrow$ Multiport beamsplitter possible
    - Experimental realization in ^{87}Rb, D1 line
      $\Rightarrow$ 2 upper levels
    - Experimentally robust; only two-photon resonance must be maintained
    - EIT condition suppresses absorbtion of the created field
    - Applications
        - All-optical routing
        - Frequency conversion
        - Quantum state engineering
- To Do:
    - Show that RATOS transfers the quantum state
    - Transfer squeezed states
    - Transfer Fock states
    - Couple in a two-mode state

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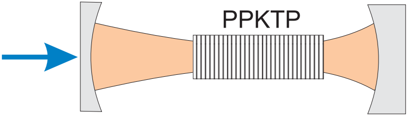
Source of non-classical light for experiments with atoms



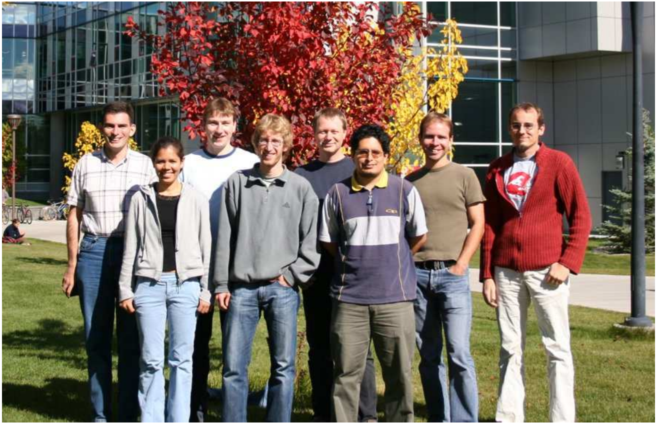
*O*ptical *P*arametric *A*mplifier

- 5 mm long PPKTP crystal
- type-I configuration
- pumped by frequency doubled Ti:Sa
- 75 mm linear resonator
- doubly resonant
- oscillation threshold $\approx 50\,\mathrm{mW}$

Properties

- narrow bandwidth ($\approx 10\,\mathrm{MHz}$)
- high brightness
- resonant to atomic transition
- squeezed light close to threshold
- heralded Fock states far below threshold

Thanks



Ph.D. & Postdoc positions available
http://qis.ucalgary.ca/quantech/

Frank Vewinger,
Eden Figueroa,
Georg Günter,
Peter Marzlin,
Alex Lvovsky

Funding:

- CIAR
- NSERC
- AIF
- CFI

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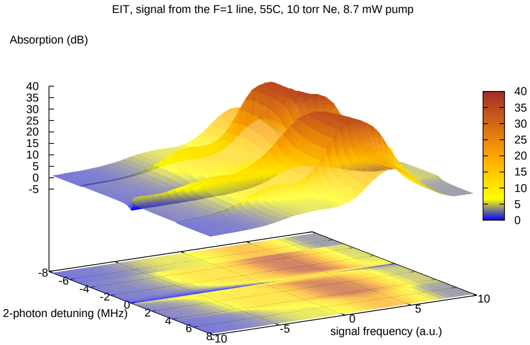
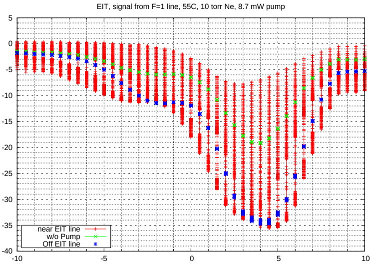
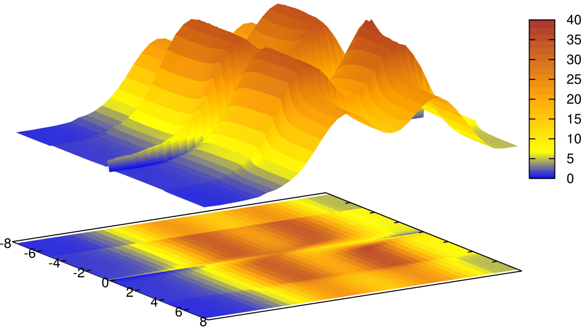
TOC

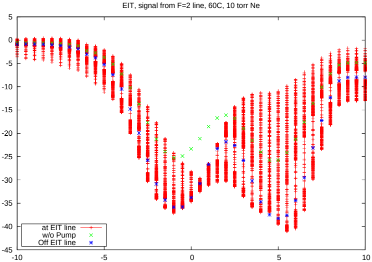
EIT, F=1


EIT, signal from the F=1 line, 55C, 10 torr Ne, 8.7 mW pump
Absorption (dB)
40
35
30
25
20
15
10
5
0
-5
2-photon detuning (MHz)
-8
-6
-4
-2
0
2
4
6
8
signal frequency (a.u.)
-10
-5
0
5
10
40
35
30
25
20
15
10
5
0


EIT, signal from F=1 line, 55C, 10 torr Ne, 8.7 mW pump
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-10
-5
0
5
10
near EIT line
w/o Pump
Off EIT line

EIT, F=2


40
35
30
25
20
15
10
5
0
-8
-6
-4
-2
0
2
4
6
8


EIT, signal from F=2 line, 60C, 10 torr Ne
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-10
-5
0
5
10
at EIT line
w/o Pump
Off EIT line