# Single Photon Generation and Phase Control with Electromagnetically Induced Transparency

2009 / 12 / 15

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$$$ NSC 96-2112-M-006-022-MY3
NSC 98-2628-M-006-002

# Outline

- Introduction to single photon generation
- Electromagnetically induced transparency (EIT)
- “Stopped” light (Quantum memory technique)
- Ultralow-light-level phase measurement
- Cross phase modulation (XPM) with EIT
- Summary & Outlook

# Introduction to single photon generation

# Single Photon Source

- ✓ Deterministic
- ✓ On demand
- ✓ High generation rate
- ✓ Narrow bandwidth
- ✓ Built-in memory

# Single Photon Source

- ✓ Nonlinear crystal (Parametric down conversion)
- ✓ Cavity-based single atom
- ✓ Quantum dot
- ✓ Atomic ensembles (many atoms system)

# Nonlinear Crystal

PHYSICAL REVIEW LETTERS

VOLUME 75 | 11 DECEMBER 1995 | NUMBER 24

## New High-Intensity Source of Polarization-Entangled Photon Pairs

Paul G. Kwiat,* Klaus Mattle, Harald Weinfurter, and Anton Zeilinger

*Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, 6020 Innsbruck, Austria*

Alexander V. Sergienko and Yanhua Shih

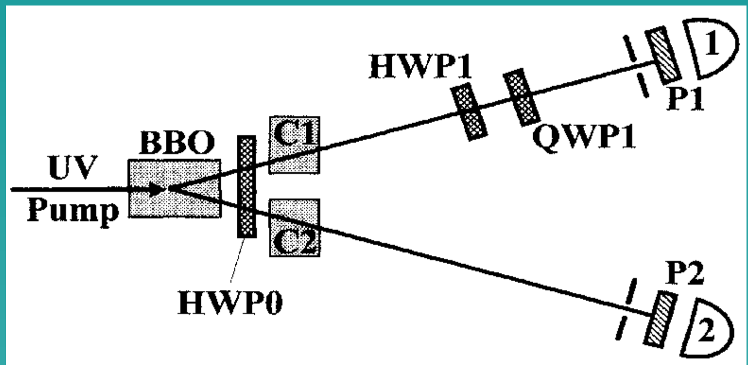
*Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland 21228*

(Received 5 July 1995)

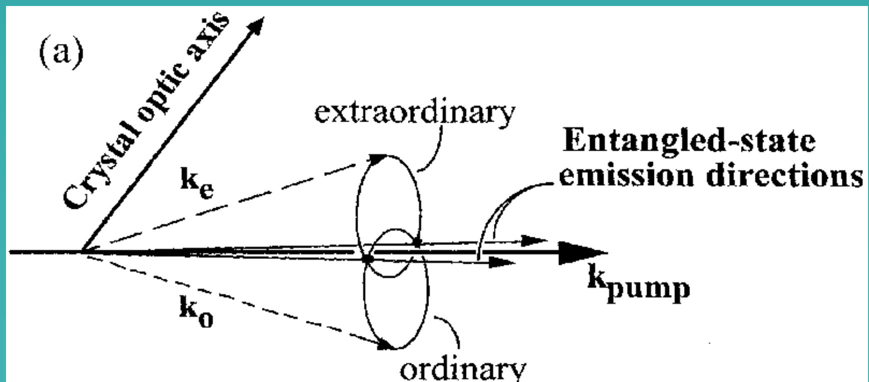
We report on a high-intensity source of polarization-entangled photon pairs with high momentum definition. Type-II noncollinear phase matching in parametric down conversion produces true entanglement: No part of the wave function must be discarded, in contrast to previous schemes. With two-photon fringe visibilities in excess of 97%, we demonstrated a violation of Bell's inequality by over 100 standard deviations in less than 5 min. The new source allowed ready preparation of all four of the EPR-Bell states.

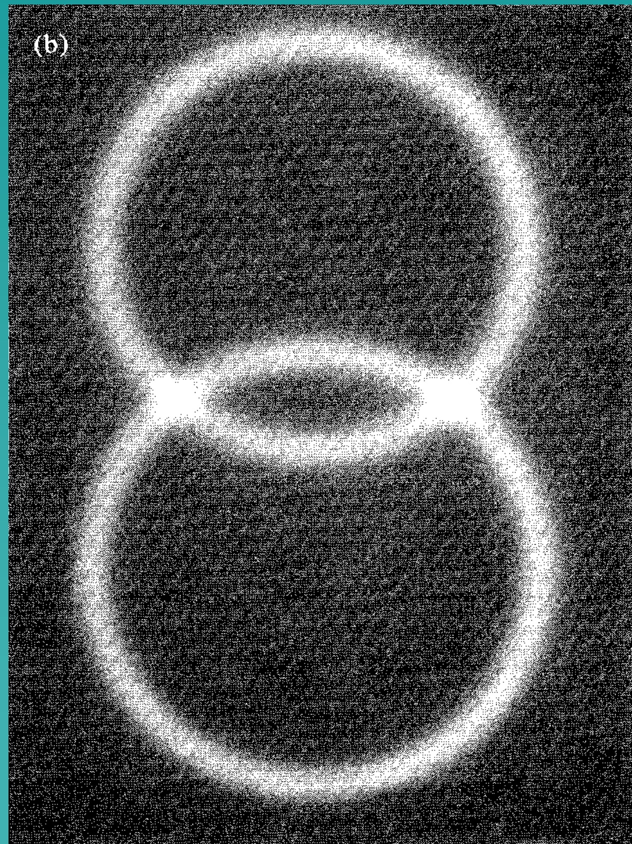
# Parametric Down Conversion

✓ Beta Barium Borate (BBO) : 硼酸鋇




✓ 351.1nm Argon ion laser (150mW)




✓ Coincidence rate > 1500 per second

-- P. G. Kwiat, K. Mattle, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. **75**, 4337 (1995)

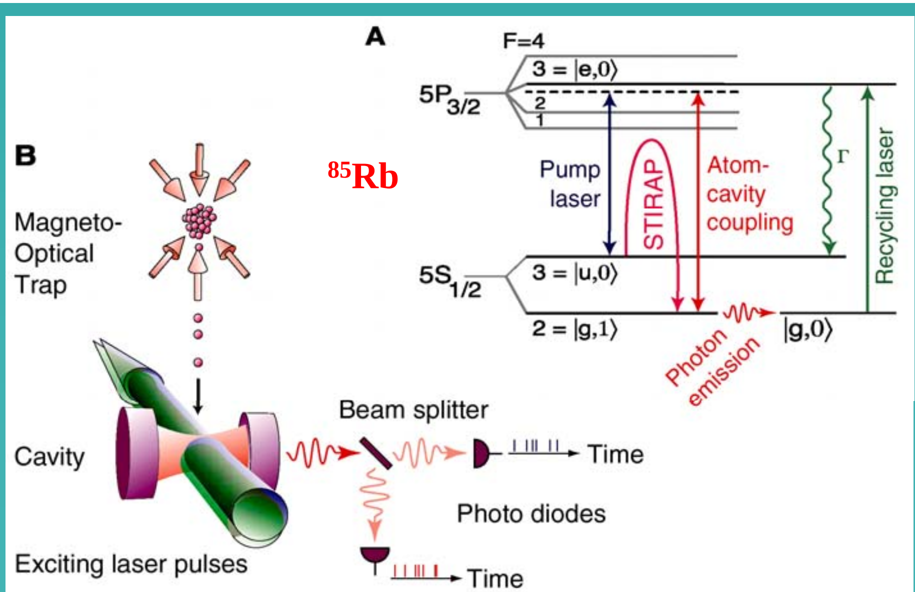
# Cavity-based Single Atom

VOLUME 89, NUMBER 6 PHYSICAL REVIEW LETTERS 5 AUGUST 2002

## Deterministic Single-Photon Source for Distributed Quantum Networking

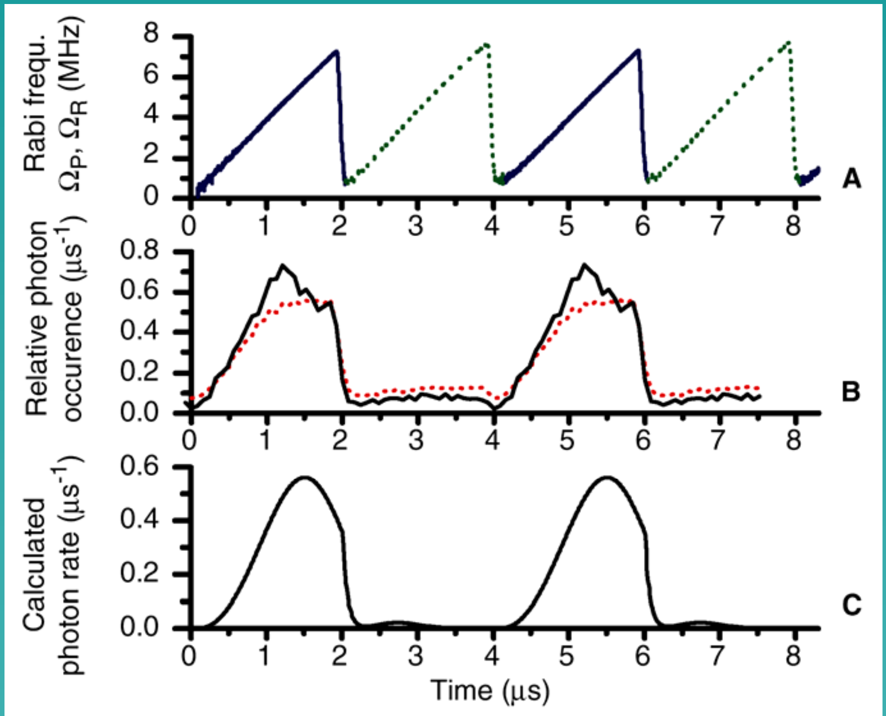
Axel Kuhn, Markus Hennrich, and Gerhard Rempe
*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
(Received 25 April 2002; published 19 July 2002)

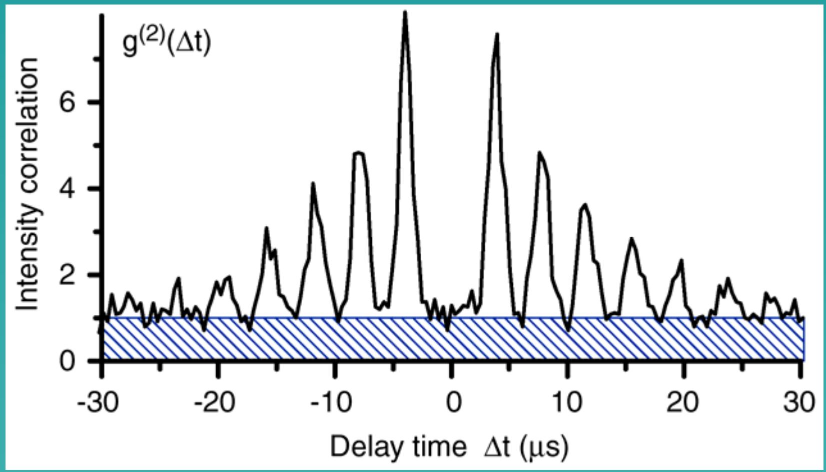
A sequence of single photons is emitted on demand from a single three-level atom strongly coupled to a high-finesse optical cavity. The photons are generated by an adiabatically driven stimulated Raman transition between two atomic ground states, with the vacuum field of the cavity stimulating one branch of the transition, and laser pulses deterministically driving the other branch. This process is unitary and therefore intrinsically reversible, which is essential for quantum communication and networking, and the photons should be appropriate for all-optical quantum information processing.




- ✓ 1mm cavity with a finesse of 60000
- ✓ $TEM_{00}$ mode waist of the cavity = 35 $\mu$m
- ✓ Velocity of atoms ~ 2 m/s
- ✓ The interaction time ~ 17.5 $\mu$s
- ✓ One mirror has a 25 times larger transmission than the other

# Experiment : Cavity-based Single Atom




- ✓ On average, 3.4 atoms per ms enter the cavity
- ✓ Single-photon generation rate ~ 15000 per second
- ✓ The correlation function oscillates with the same periodicity as the sequence of pump pulses

-- Axel Kuhn, Markus Hennrich, and Gerhard Rempe, Phys. Rev. Lett. **89**, 067901 (2002)

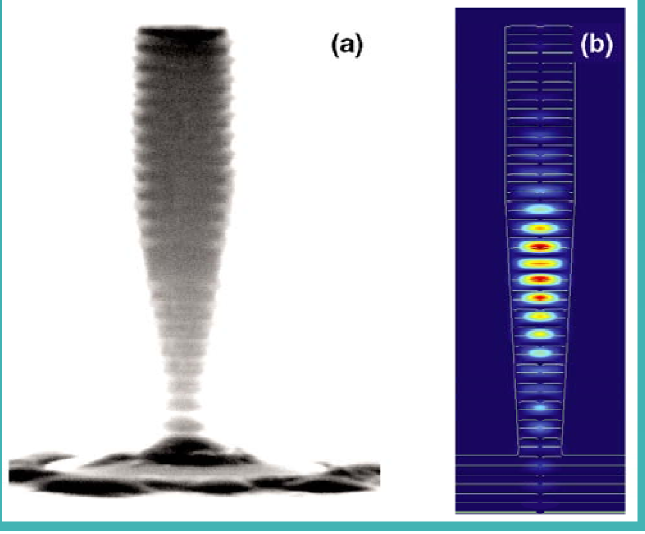
# Quantum Dot

VOLUME 89, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 2002

## Efficient Source of Single Photons: A Single Quantum Dot in a Micropost Microcavity

Matthew Pelton,* Charles Santori, Jelena Vučković, Bingyang Zhang,† Glenn S. Solomon,‡
Jocelyn Plant, and Yoshihisa Yamamoto†
*Quantum Entanglement Project, ICORP, JST, E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305*
(Received 8 August 2002; published 13 November 2002)

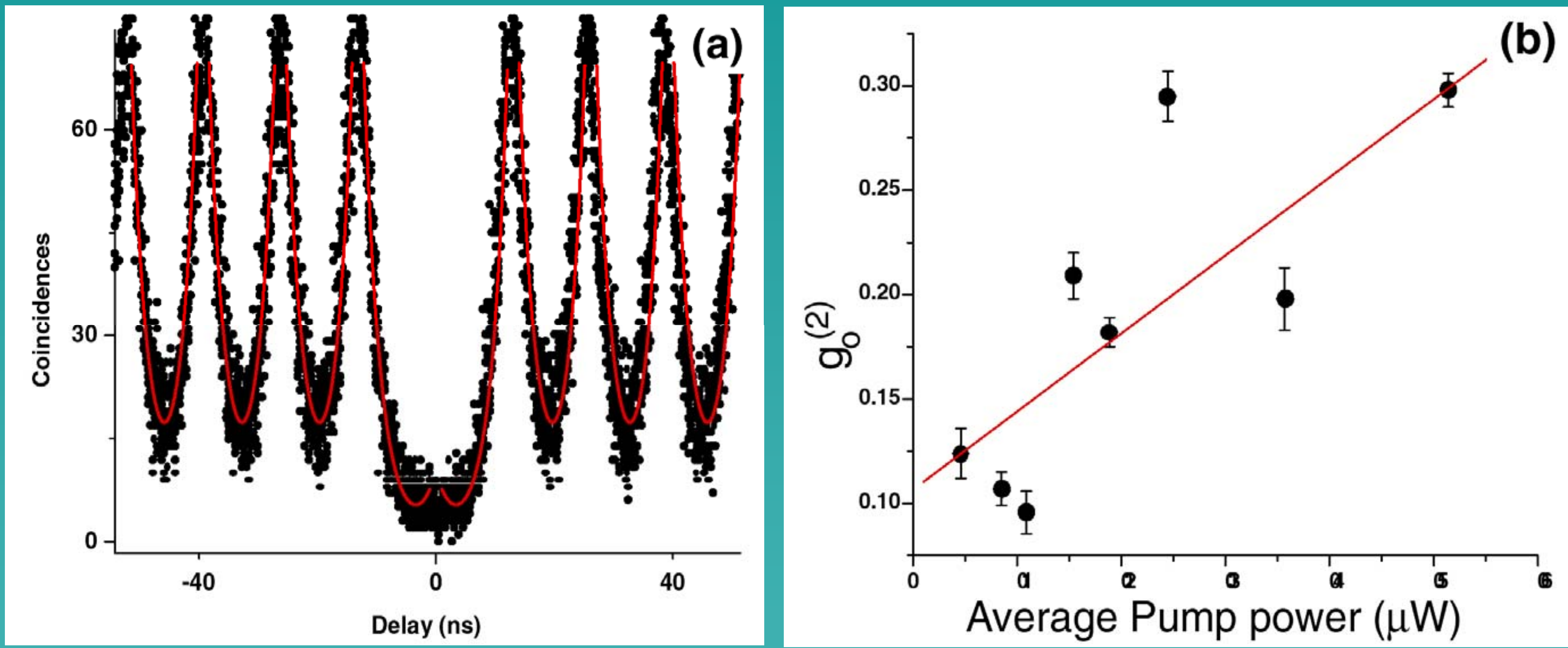
We have demonstrated efficient production of triggered single photons by coupling a single semiconductor quantum dot to a three-dimensionally confined optical mode in a micropost microcavity. The efficiency of emitting single photons into a single-mode traveling wave is approximately 38%, which is nearly 2 orders of magnitude higher than for a quantum dot in bulk semiconductor material. At the same time, the probability of having more than one photon in a given pulse is reduced by a factor of 7 as compared to light with Poissonian photon statistics.




- ✓ Distributed-Bragg Reflector (DBR) microcavity
- ✓ Contain self-assembled InAs Quantum dots

FIG. 1 (color). (a) Scanning-electron microscope (SEM) image of a micropost microcavity with a top diameter of 0.6 $\mu$m and a height of 4.2 $\mu$m. (b) Color-scale representation of the amplitude of the electric field for the fundamental mode of the micropost microcavity, as calculated by the finite-difference time-domain method. The profile of the modeled post matches the profile of the real posts as measured from SEM images.

# Experiment : Quantum Dot

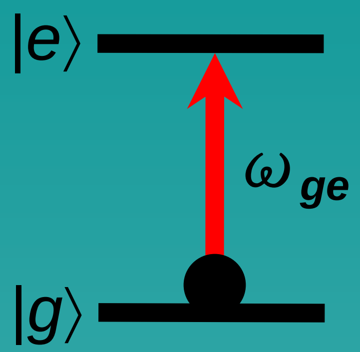



✓ Operation temperature 5 K

✓ High single-photon generation rate

-- Matthew Pelton *et al.*, Phys. Rev. Lett. **89**, 233602 (2002)

# Interaction between Light and Single Atom

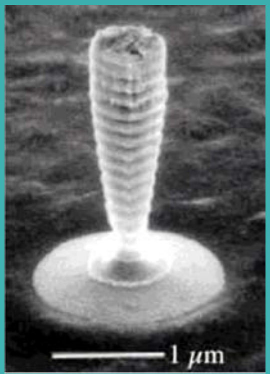


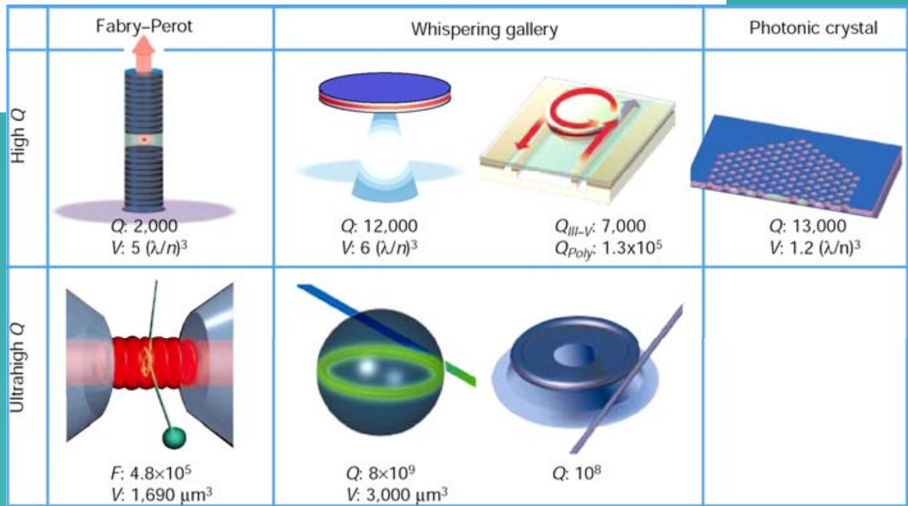

Resonant interaction of an atom with light allows coherent manipulation of light and atomic states

✓However, single atom absorption cross-section ~ $\lambda^2$

✓Cavity QED : fascinating but not easy experiment!!


K. Vahala (Caltech)
J.Kimble (Caltech)
G.Rempe (MPQ)
H.Walter (MPQ)
Y.Yamamoto (Stanford)




-- Kerry J. Vahala, Nature 424, 839 (2003)

# Atomic Ensembles-Light Interaction

Interaction of light field and many atoms is strong (collective enhancement), but incoherent (spontaneous emission)

✓Need : techniques for coherent control of resonant optical properties

✓Idea : suppress the resonant absorption & coherent control light propagating in many atom system (atomic ensembles)

✓**E**lectromagnetically **I**nduced **T**ransparency (EIT)

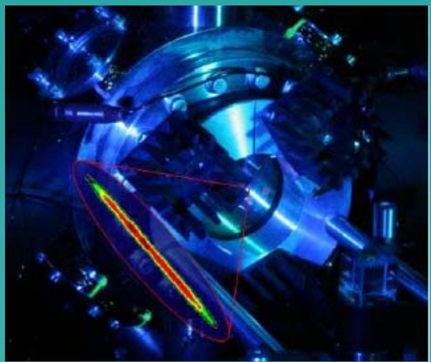
Coupled propagation of photonic and spin wave : dark-state polaritons

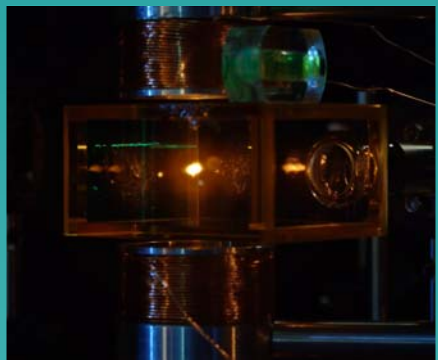
-- M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. **84**, 5094 (2000)

# Experiment : Atomic Ensembles

Cold atoms

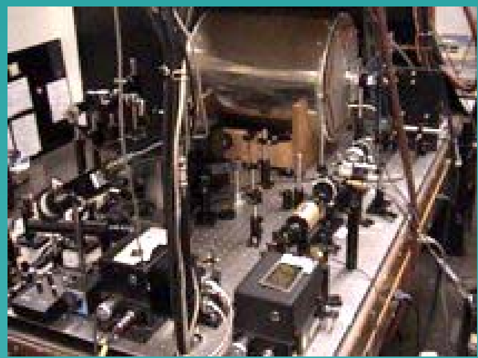
Hot atoms





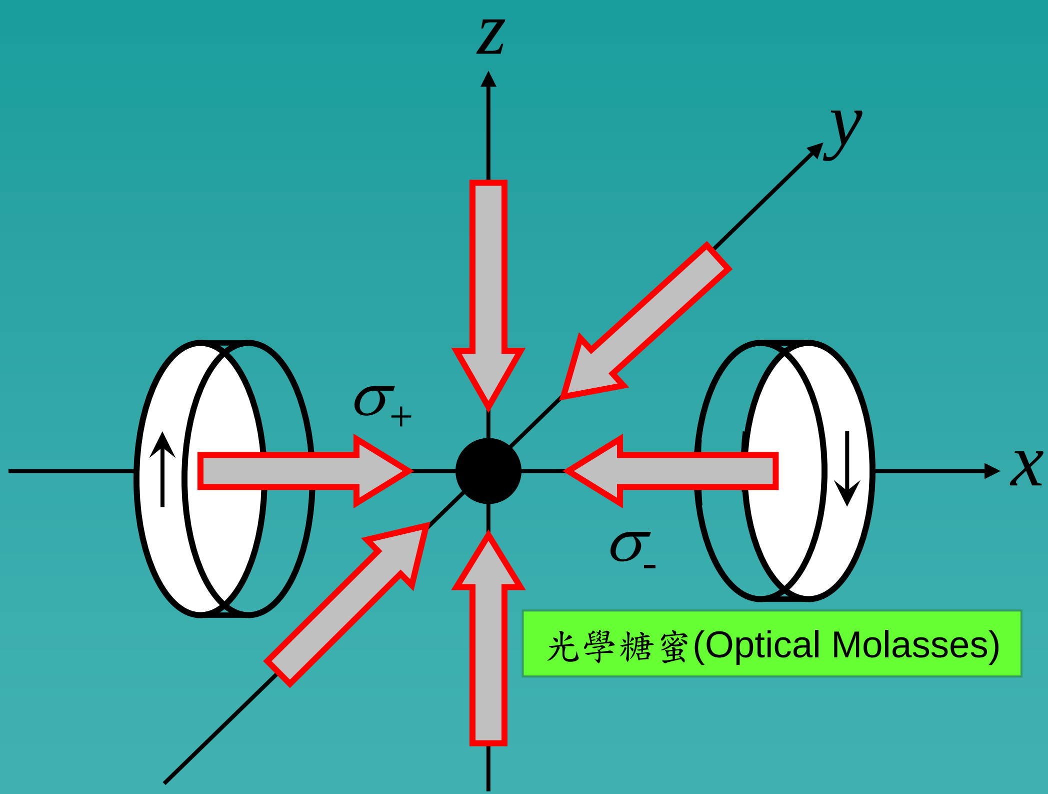
Kimble's group
Caltech

Our group
U. Cheng Kung



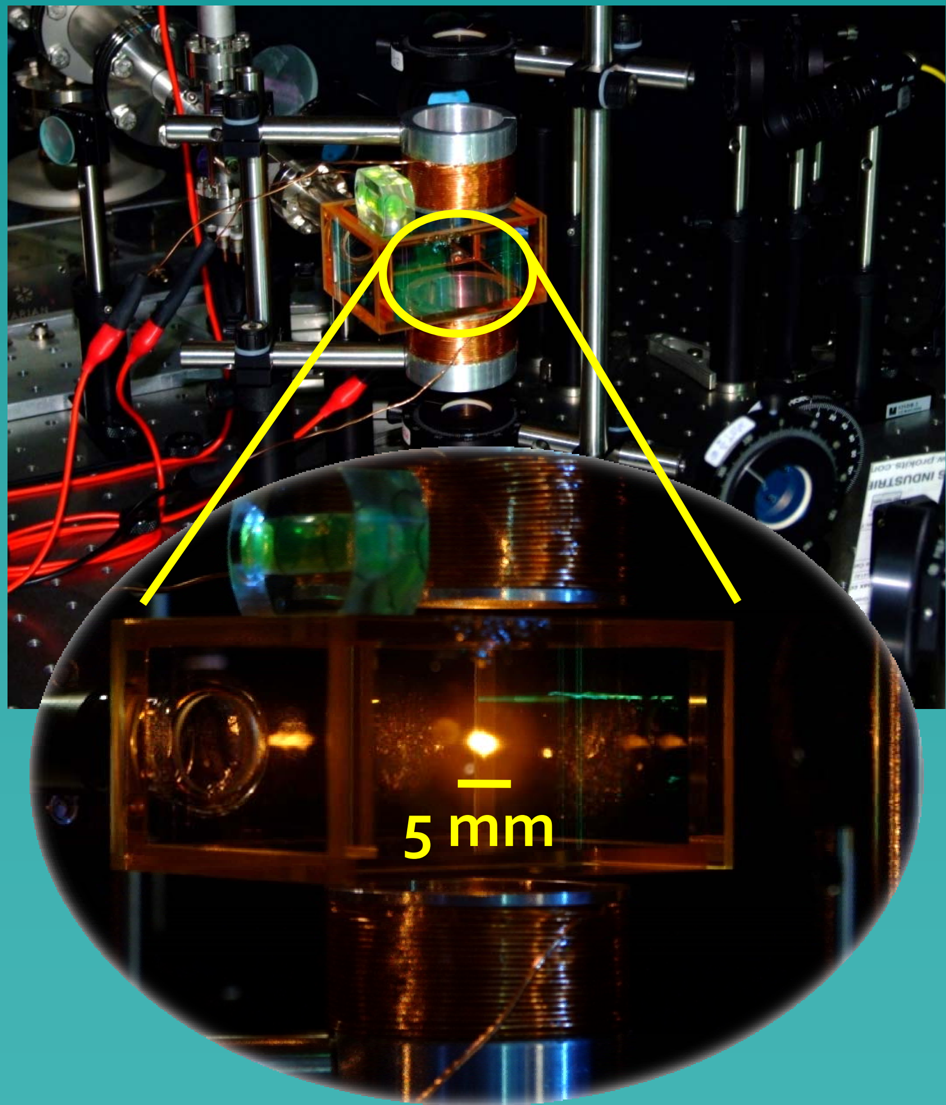
Walsworth's group
U. Harvard

# Magneto-optical Trap (MOT)




Ultracold atoms produced by laser cooling and trapping

# $^{87}$Rb Cold Atoms



# Manipulating atoms with photons*

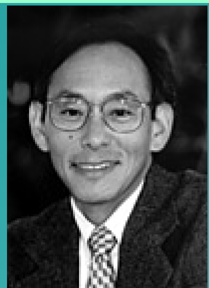
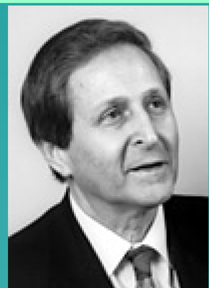
Claude N. Cohen-Tannoudji

*Collège de France et Laboratoire Kastler Brossel† de l'Ecole Normale Supérieure, 75231 Paris Cedex 05, France*

Reviews of Modern Physics, Vol. 70, No. 3, July 1998 0034-6861/98/70(3)/707(13)/$17.60  

## The Nobel Prize in Physics 1997

"for development of methods to cool and trap atoms with laser light"

|  |  |  |
|---|---|---|
| **Steven Chu** | **Claude Cohen-Tannoudji** | **William D. Phillips** |
| 1/3 of the prize | 1/3 of the prize | 1/3 of the prize |
| USA | France | USA |
| Stanford University<br>Stanford, CA, USA | Collège de France; École Normale Supérieure<br>Paris, France | National Institute of Standards and Technology<br>Gaithersburg, MD, USA |
| b. 1948 | b. 1933<br>(in Constantine, Algeria) | b. 1948 |

Nobelprize.org

Single photon generation with atomic ensembles

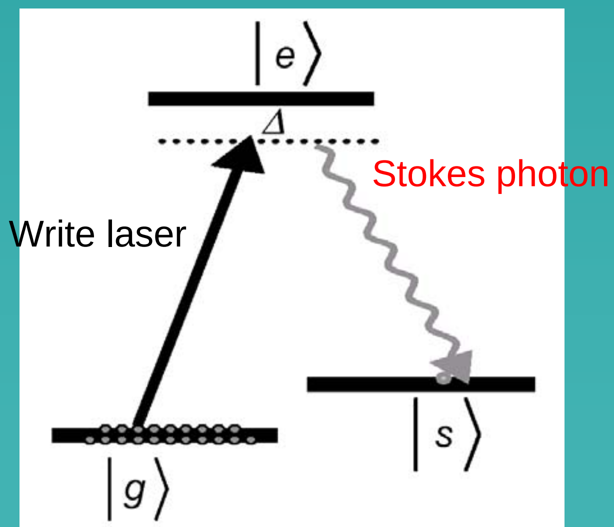
(**DLCZ** scheme)

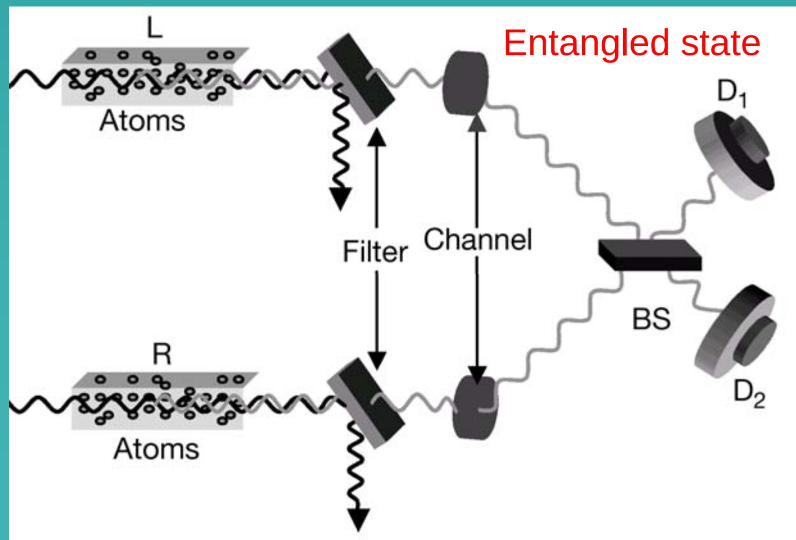
# DLCZ scheme

## Long-distance quantum communication with atomic ensembles and linear optics

**L.-M. Duan*†, M. D. Lukin‡, J. I. Cirac* & P. Zoller***

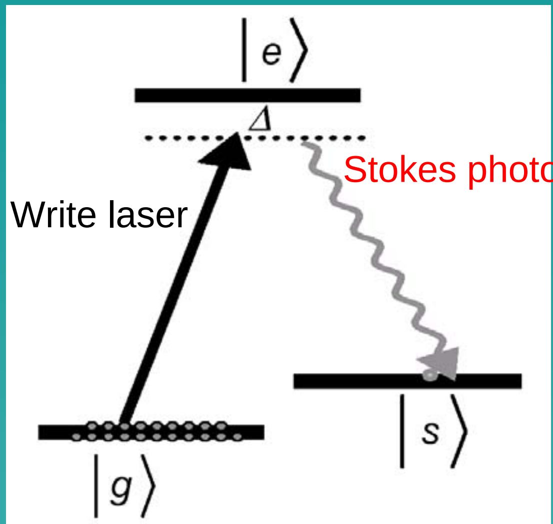
* *Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*
† *Laboratory of Quantum Communication and Computation, USTC, Hefei 230026, China*
‡ *Physics Department and ITAMP, Harvard University, Cambridge, Massachusetts 02138, USA*




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

# "Collective" atomic spin state




✓Write pulse and 1 Stokes photon lead to state with 1 quantum of atomic ensemble excitation

Initial state

$$|0_a\rangle\,|0_p\rangle = \underbrace{\otimes_i\ |g\rangle_i}_{\text{All atoms in ground state } g} \otimes \underbrace{|0_p\rangle}_{\text{Zero photons in Stokes mode}}$$

$$S \equiv (1/\sqrt{N_a})\Sigma_i |g\rangle_i \langle s|$$

Collective atomic mode operator

Nothing happen

1 quantum of excitation in Stokes mode

$$|\phi\rangle = \underline{|0_a\rangle\,|0_p\rangle} + \sqrt{p_c}\,\underbrace{S^\dagger}_{\text{1 quantum of excitation in collective atomic mode}} \overbrace{a^\dagger}^{\text{1 quantum of excitation in Stokes mode}} |0_a\rangle\,|0_p\rangle + o(p_c)$$

1 quantum of excitation in collective atomic mode

**Single photon generation on demand !!!**

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

# Experiment : DLCZ Scheme

VOLUME 92, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 28 MAY 2004

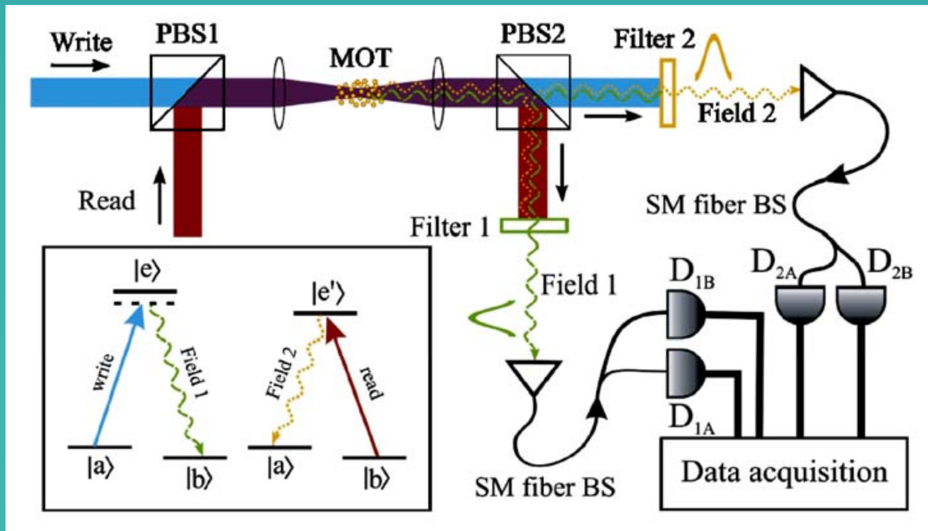
## Single-Photon Generation from Stored Excitation in an Atomic Ensemble

C.W. Chou, S.V. Polyakov, A. Kuzmich,* and H. J. Kimble

*Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, USA*

(Received 21 January 2004; published 25 May 2004)

Single photons are generated from an ensemble of cold Cs atoms via the protocol of Duan *et al.* [Nature (London) **414**, 413 (2001)]. Conditioned upon an initial detection from field 1 at 852 nm, a photon in field 2 at 894 nm is produced in a controlled fashion from excitation stored within the atomic ensemble. The single-quantum character of field 2 is demonstrated by the violation of a Cauchy-Schwarz inequality, namely $w(1_2, 1_2|1_1) = 0.24 \pm 0.05 \not\geq 1$, where $w(1_2, 1_2|1_1)$ describes the detection of two events $(1_2, 1_2)$ conditioned upon an initial detection $1_1$, with $w \to 0$ for single photons.



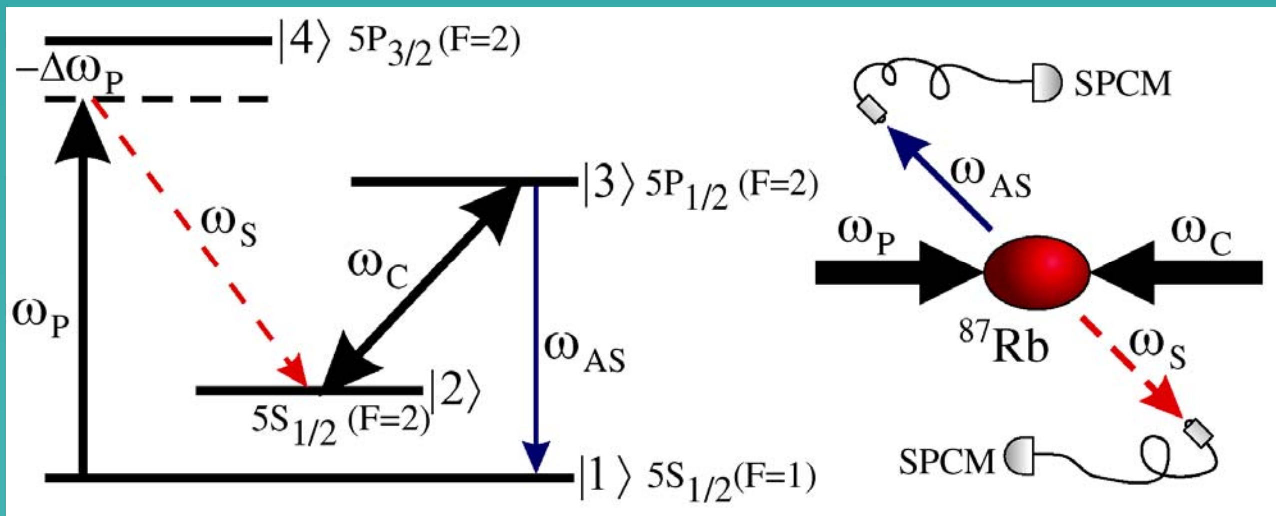
# Single-photon Generation via Four-wave Mixing

VOLUME 93, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 29 OCTOBER 2004

## Frequency Mixing Using Electromagnetically Induced Transparency in Cold Atoms

Danielle A. Braje,* Vlatko Balić, Sunil Goda, G. Y. Yin, and S. E. Harris
*Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*
(Received 17 June 2004; published 29 October 2004)

We report the first experimental demonstration of four-wave mixing using electromagnetically induced transparency in cold atoms. Backward-wave, phase-matched difference-frequency conversion is achieved at optical powers of a few nanowatts and at energies of less than a picojoule.



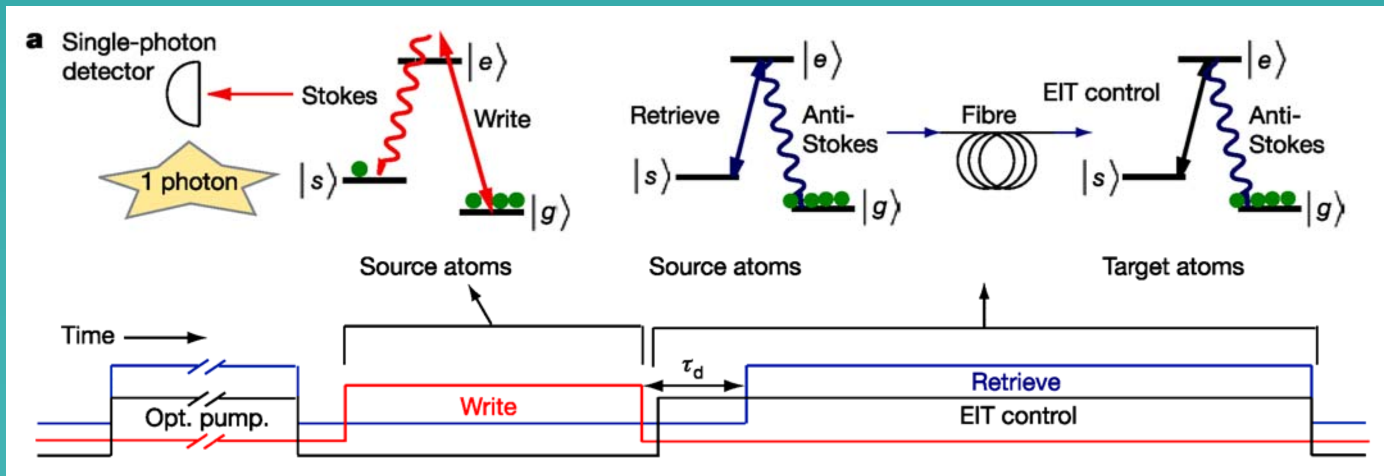
# Single Photon Storage (Hot atoms)

Vol 438|8 December 2005|**doi:10.1038/nature04327** nature

LETTERS

## Electromagnetically induced transparency with tunable single-photon pulses

M. D. Eisaman[1], A. André[1], F. Massou[1], M. Fleischhauer[1,2,3], A. S. Zibrov[1,2,4] & M. D. Lukin[1]




M. D. Eisaman *et al.*, Nature (London) **438**, 837 (2005)

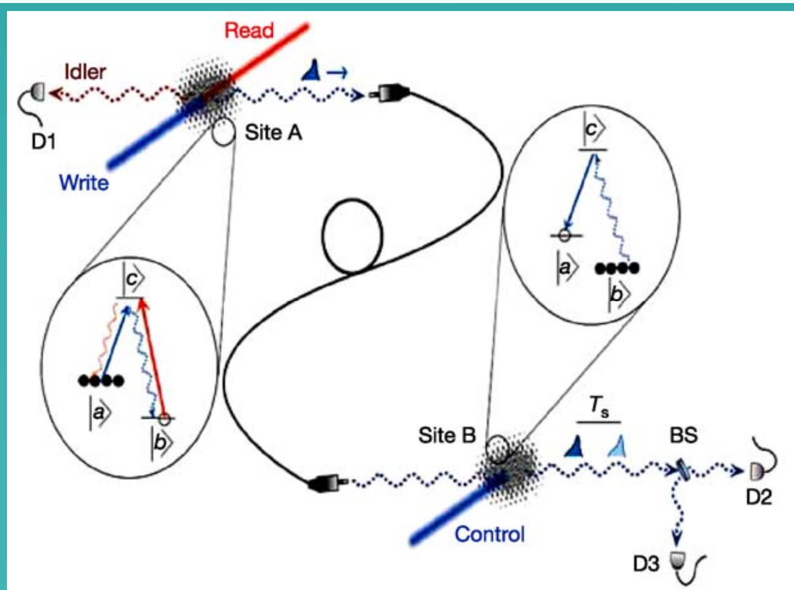
# Single Photon Storage (Cold atoms)

Vol 438|8 December 2005|**doi:10.1038/nature04315** nature

LETTERS

## Storage and retrieval of single photons transmitted between remote quantum memories

T. Chanelière[1], D. N. Matsukevich[1], S. D. Jenkins[1], S.-Y. Lan[1], T. A. B. Kennedy[1] & A. Kuzmich[1]




T. Chaneliere *et al*., Nature (London) **438**, 833 (2005).

# Electromagnetically Induced Transparency

# Electromagnetically Induced Transparency

VOLUME 64, NUMBER 10 PHYSICAL REVIEW LETTERS 5 MARCH 1990

## Nonlinear Optical Processes Using Electromagnetically Induced Transparency

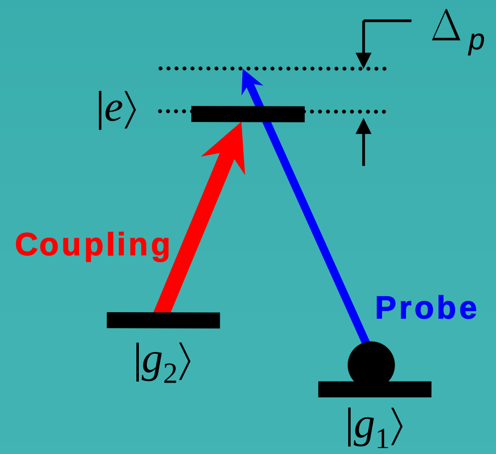
S. E. Harris, J. E. Field, and A. Imamoğlu

*Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305*

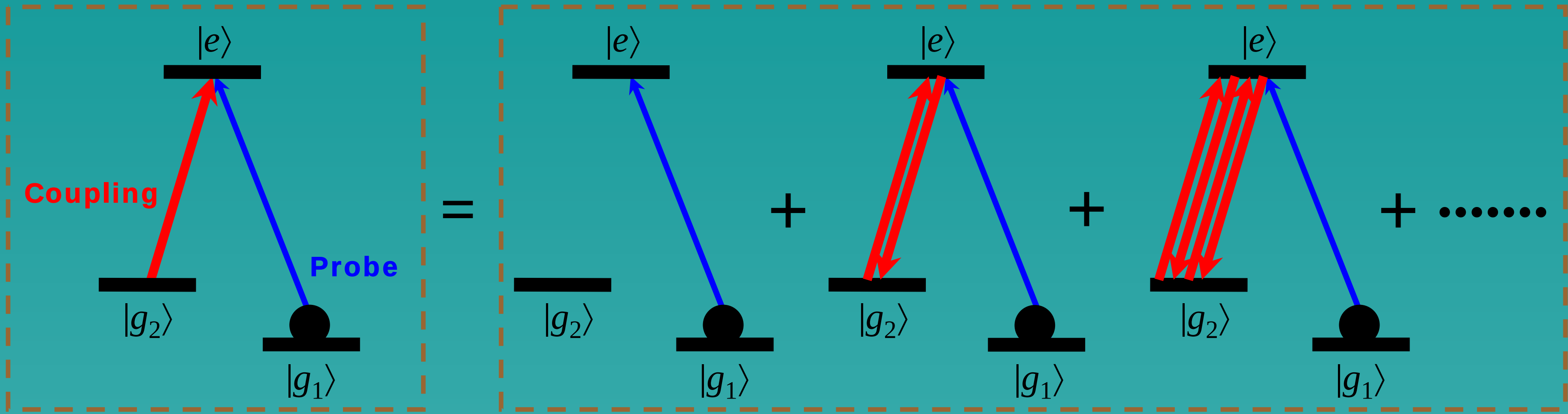
(Received 27 December 1989)

We show that by applying a strong-coupling field between a metastable state and the upper state of an allowed transition to ground one may obtain a resonantly enhanced third-order susceptibility while at the same time inducing transparency of the media. An improvement in conversion efficiency and parametric gain, as compared to weak-coupling field behavior, of many orders of magnitude is predicted.

PACS numbers: 42.65.Ky, 42.50.Hz, 42.50.Qg



# EIT : Quantum Interference

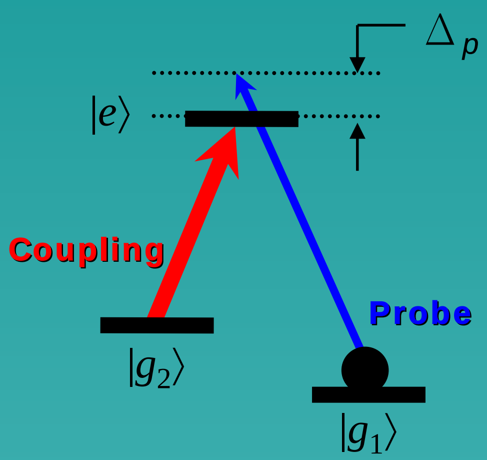



| | *path i* | *path ii* | *path iii* | ······· |
|---|---|---|---|---|
| Transition Amplitudes : | $A_i$ | $A_{ii}$ | $A_{iii}$ | ······· |

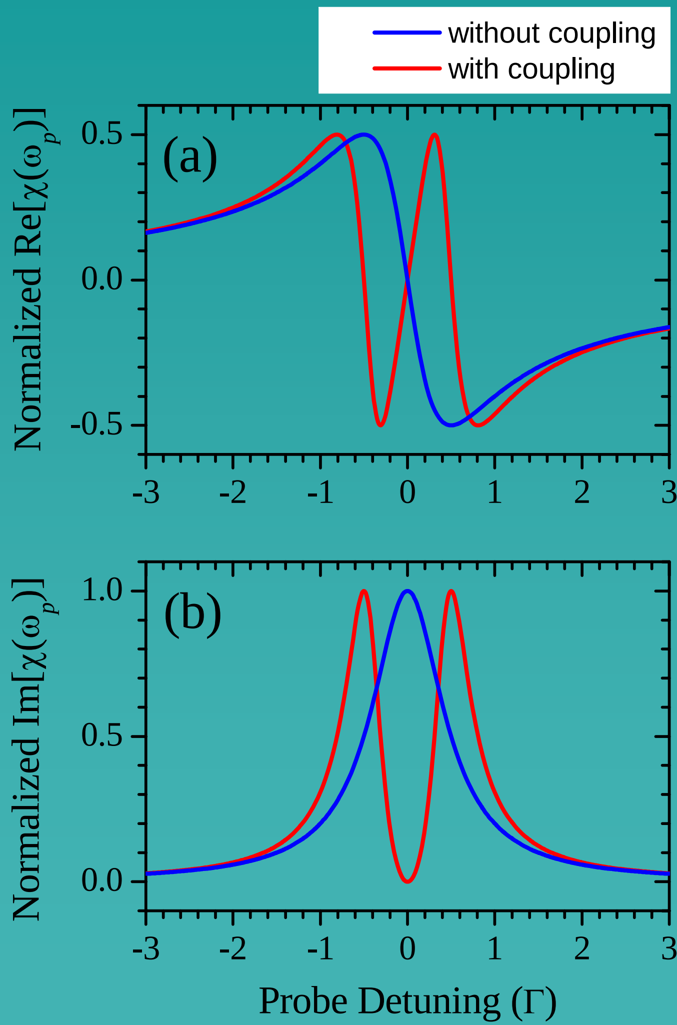
✓ Transition probability of $|g_1\rangle \rightarrow |e\rangle = |A_i + A_{ii} + A_{iii} + \cdots\cdots|^2$

✓ EIT is the destructive interference between $A_i$ , $A_{ii}$ , $A_{iii}$ , ·······
$\Rightarrow$ The probe absorption is suppressed.

# EIT Spectrum




$$V_g \equiv \frac{d\omega}{dk} = \frac{c}{n + \boxed{\omega \frac{dn}{d\omega}}}$$



VOLUME 66, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 1991

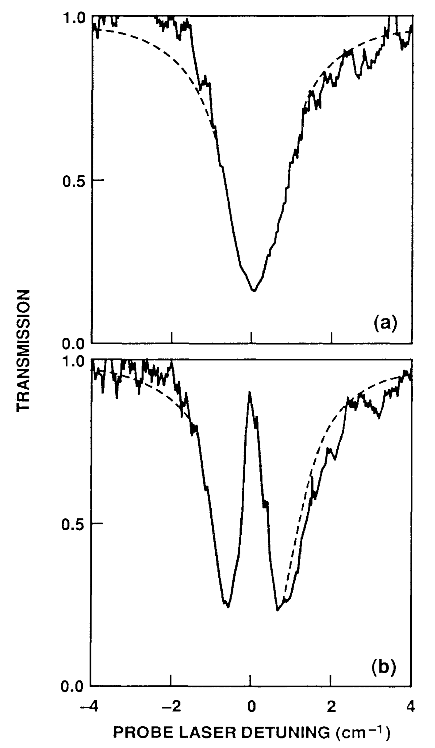
# Observation of Electromagnetically Induced Transparency

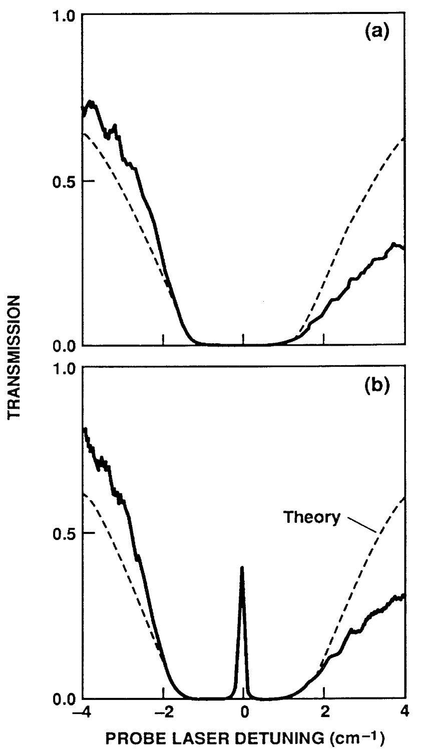
K.-J. Boller, A. Imamoğlu, and S. E. Harris

*Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305*

(Received 12 December 1990)

We report the first demonstration of a technique by which an optically thick medium may be rendered transparent. The transparency results from a destructive interference of two dressed states which are created by applying a temporally smooth coupling laser between a bound state of an atom and the upper state of the transition which is to be made transparent. The transmittance of an autoionizing (ultraviolet) transition in Sr is changed from exp(−20) without a coupling laser present to exp(−1) in the presence of a coupling laser.



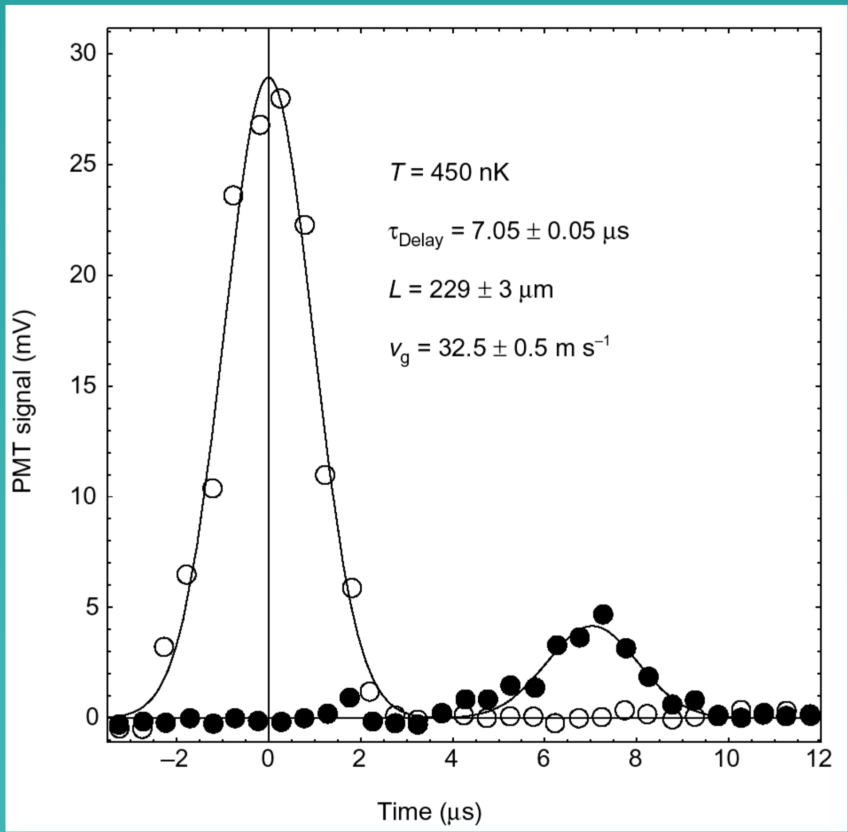



# "Slow Light" in Cold Na Atoms


Hau group : Cover of Nature associated with
article in Nature **397**, 594 (1999)

**Light speed reduction to 17 metres per second in an ultracold atomic gas**

Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§

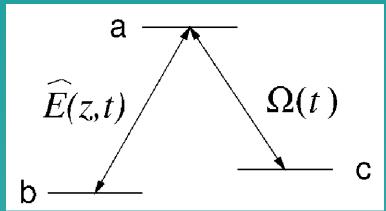


"Stopped" light (Quantum memory technique)

VOLUME 84, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY 2000

# Dark-State Polaritons in Electromagnetically Induced Transparency

M. Fleischhauer[1] and M. D. Lukin[2]
[1]*Sektion Physik, Ludwig-Maximilians-Universität München, Theresienstrasse 37, D-80333 München, Germany*
[2]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
(Received 26 January 2000)




$$\hat{\Psi}(z,t) = \cos\theta(t)\hat{E}(z,t) - \sin\theta(t)\sqrt{N}\,\hat{\sigma}_{bc}(z,t)$$

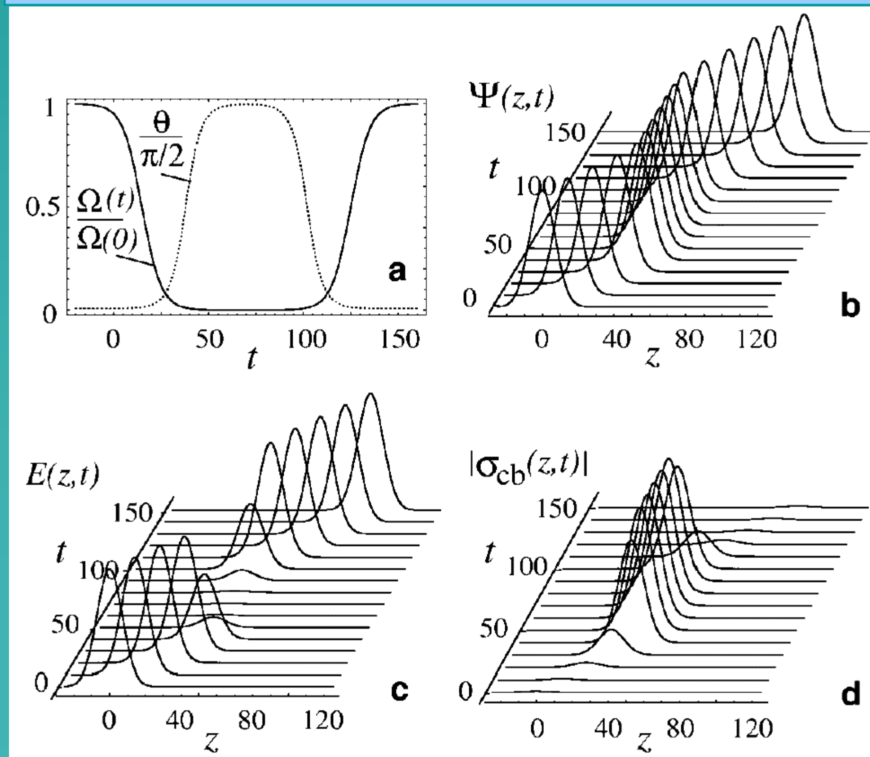
$$\cos\theta(t) = \frac{\Omega(t)}{\sqrt{\Omega^2(t) + g^2N}},$$

$$\sin\theta(t) = \frac{g\sqrt{N}}{\sqrt{\Omega^2(t) + g^2N}}.$$

Strong coupling field ($\theta \to 0$) :
Polaritons : purely photonic wave

Weak coupling field ($\theta \to \pi/2$) :
Polaritons : larger parts in spin wave

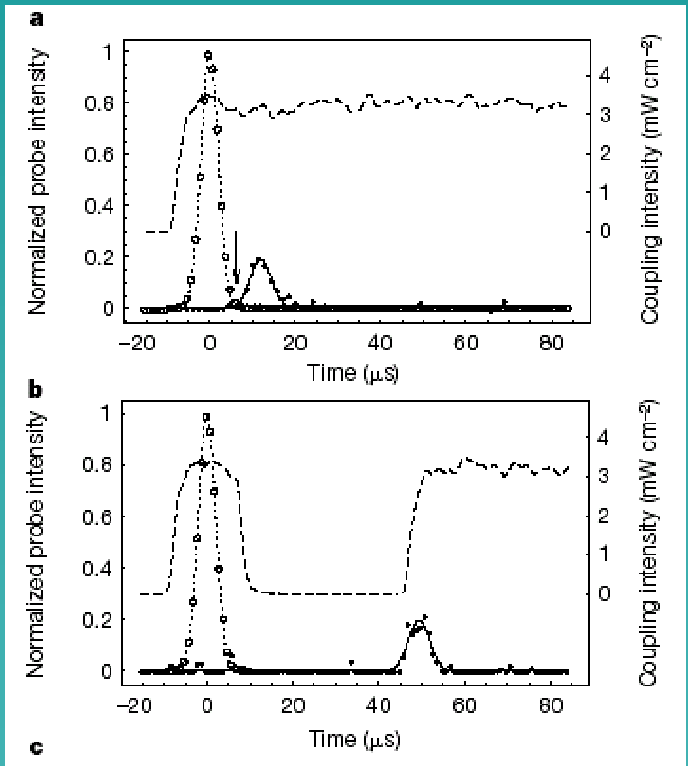
Dark-State Polaritons :
Coupled propagation of photonic and spin wave




-- M. Fleischhauer and M. D. Lukin, Phys. Rev. Lett. 84, 5094 (2000)

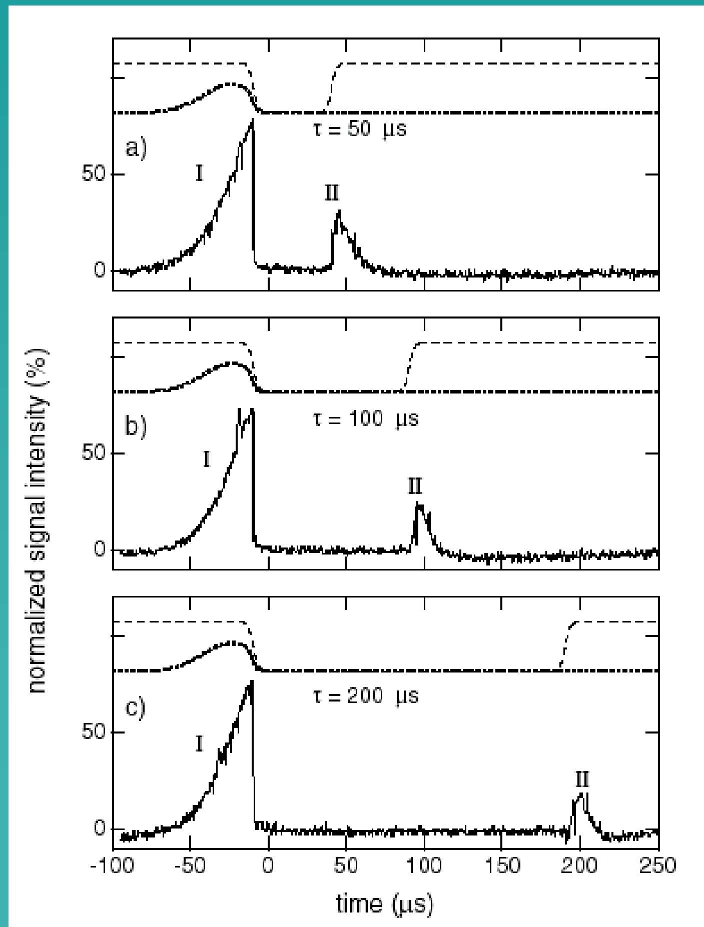
# Light Storage and Retrieval (Experiment)

**Cold atoms**



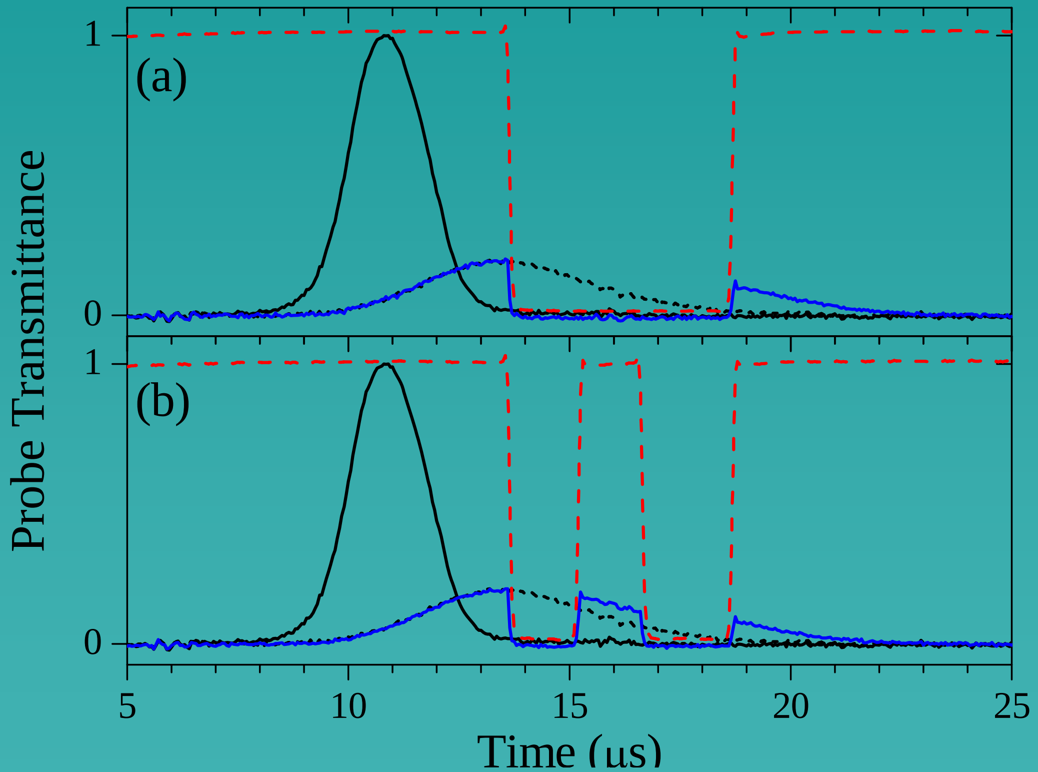

C. Liu t *al*. Nature 409, 490 (2001)

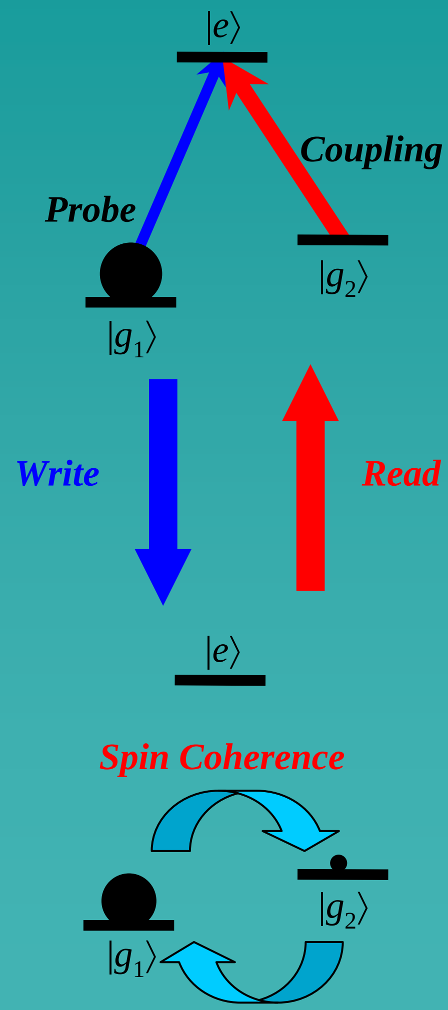
**Hot atoms**




D. Phillips *et al*. PRL 86, 783 (2001)

# Light Storage and Retrieval Twice (Reversible)




Storage time ~ 15 $\mu$s

# Images Storage

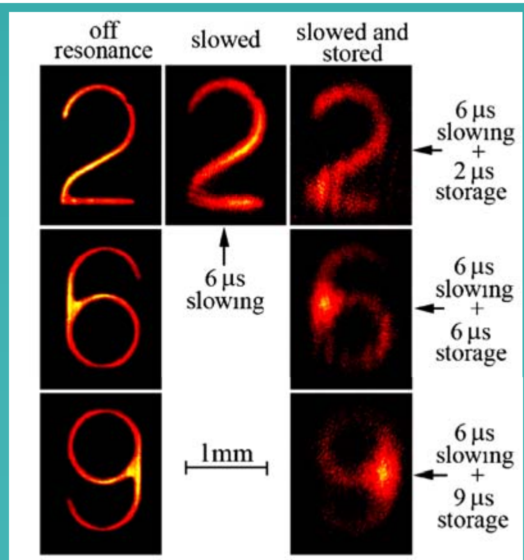
PRL **100,** 223601 (2008) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2008

## Storing Images in Warm Atomic Vapor

M. Shuker,[1] O. Firstenberg,[1] R. Pugatch,[2] A. Ron,[1] and N. Davidson[2]

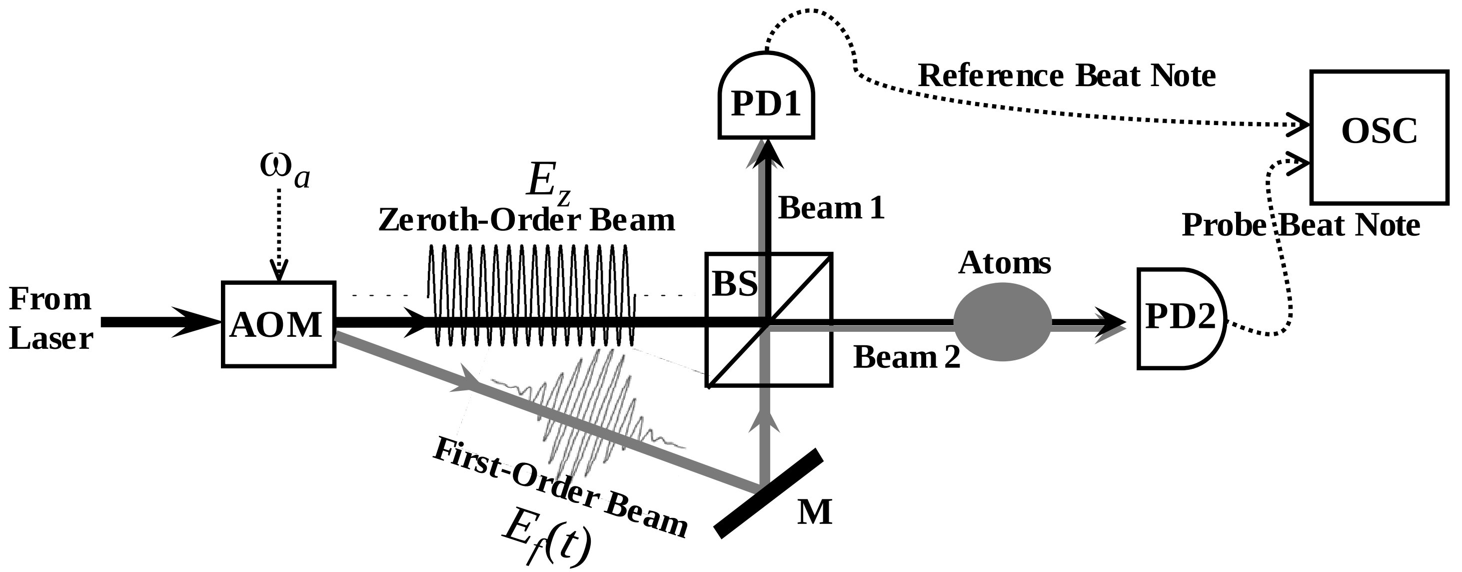
[1]*Department of Physics, Technion-Israel Institute of Technology, Haifa 32000, Israel*
[2]*Department of Physics of Complex Systems, Weizmann Institute of Science, Rehovot 76100, Israel*
(Received 13 December 2007; published 5 June 2008)

Reversible and coherent storage of light in an atomic medium is a promising method with possible applications in many fields. In this work, arbitrary two-dimensional images are slowed and stored in warm atomic vapor for up to 30 $\mu$s, utilizing electromagnetically induced transparency. Both the intensity and the phase patterns of the optical field are maintained. The main limitation on the storage resolution and duration is found to be the diffusion of atoms. A technique analogous to phase-shift lithography is employed to diminish the effect of diffusion on the visibility of the reconstructed image.



Phase ?

# Beat-note Interferometer



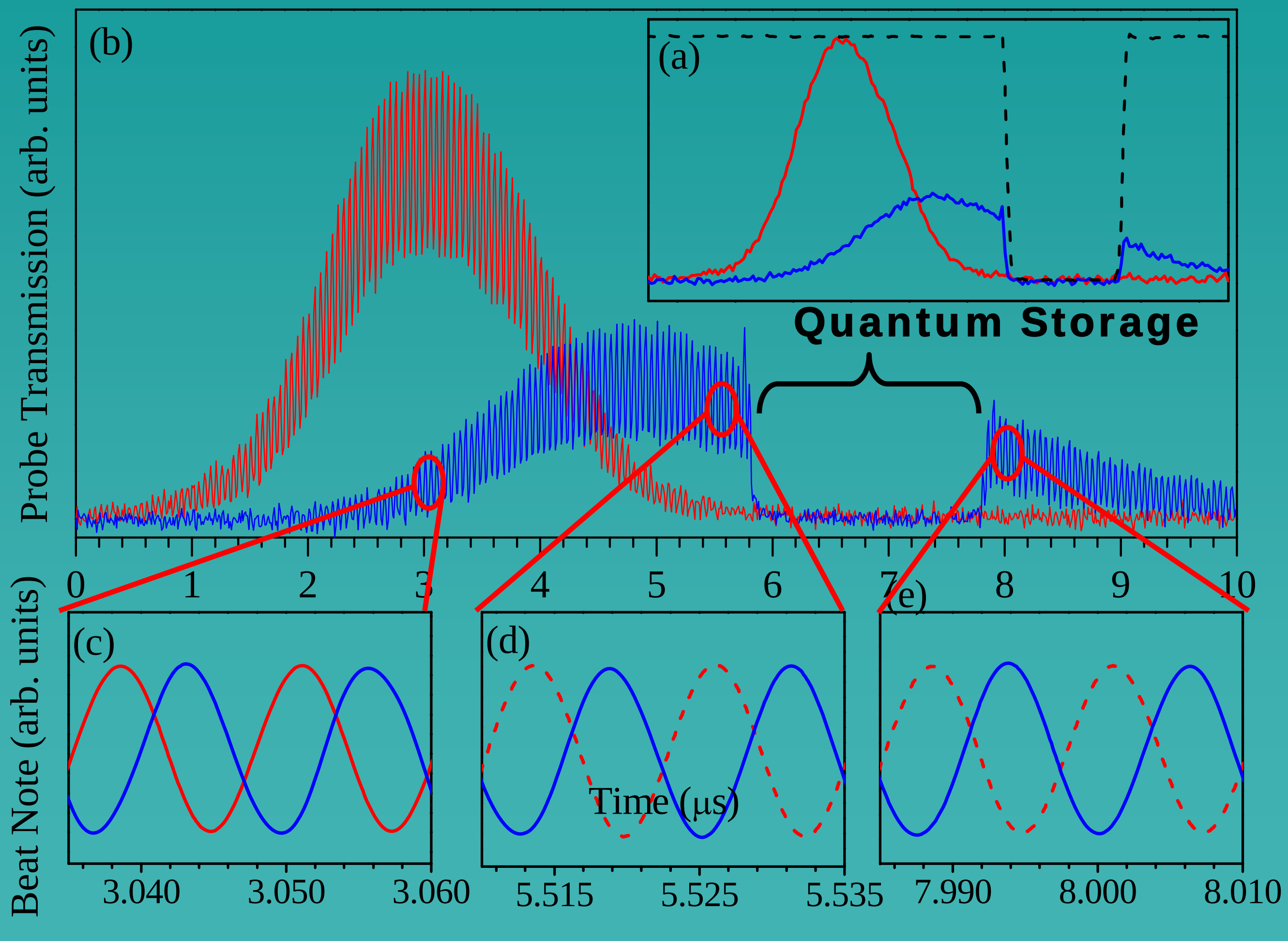

Reference Beat Note: $E_z^2 + E_f(t)^2 + 2E_z E_f(t)\cos(\omega_a t+\varphi_r)$

Probe Beat Note: $E_z^2 + E_f(t)^2 + 2E_z E_f(t)\cos(\omega_a t+\varphi_p+\Delta\varphi)$

- $\varphi_r$ and $\varphi_p$ are the phases that result from the optical paths, the AOM switching, or other factors.
- $\Delta\varphi$ is the phase shift induced by the atoms.
- Although $\varphi_r$ and $\varphi_p$ vary from one pulse to another, their difference is always fixed.

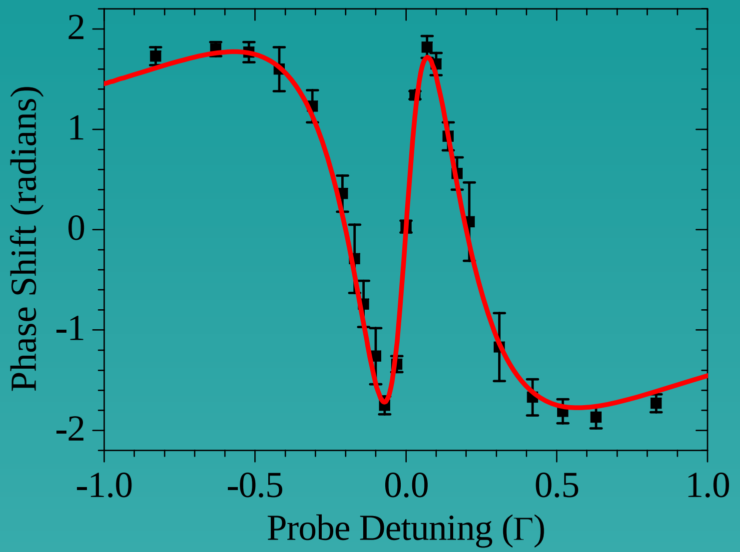
Phys. Rev. A **72**, 033812 (2005)

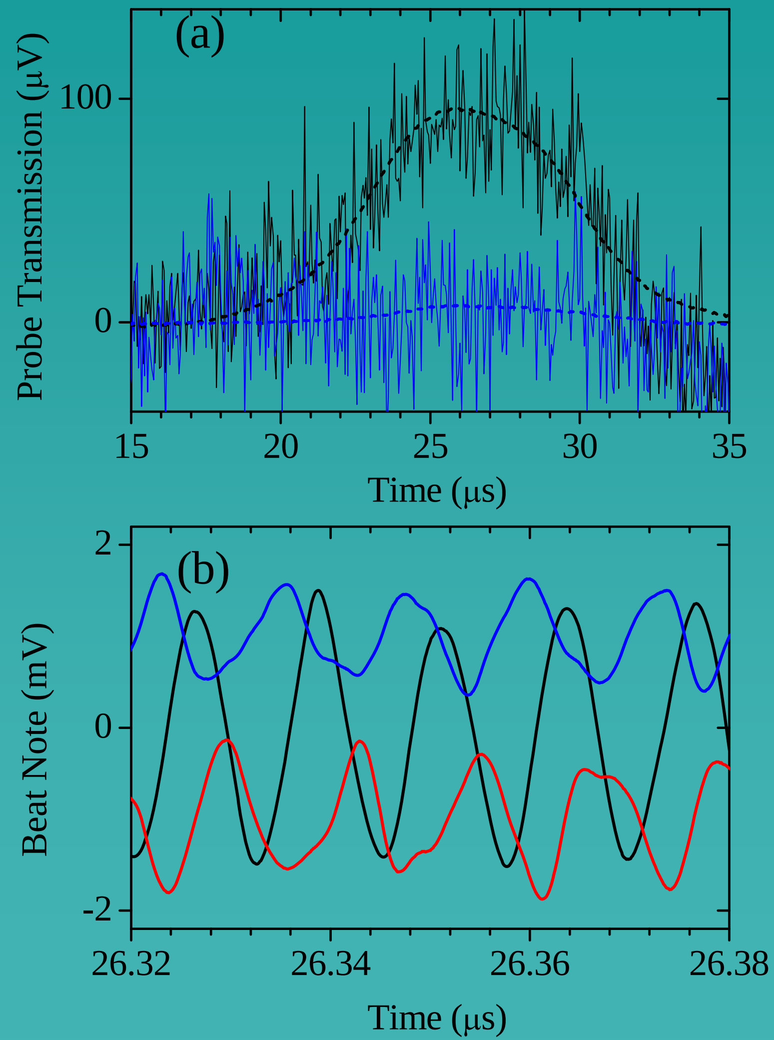
# Phase Coherence of Storage and Retrieval




Phys. Rev. A **72**, 033812 (2005)

# Low-light-level Phase Measurement

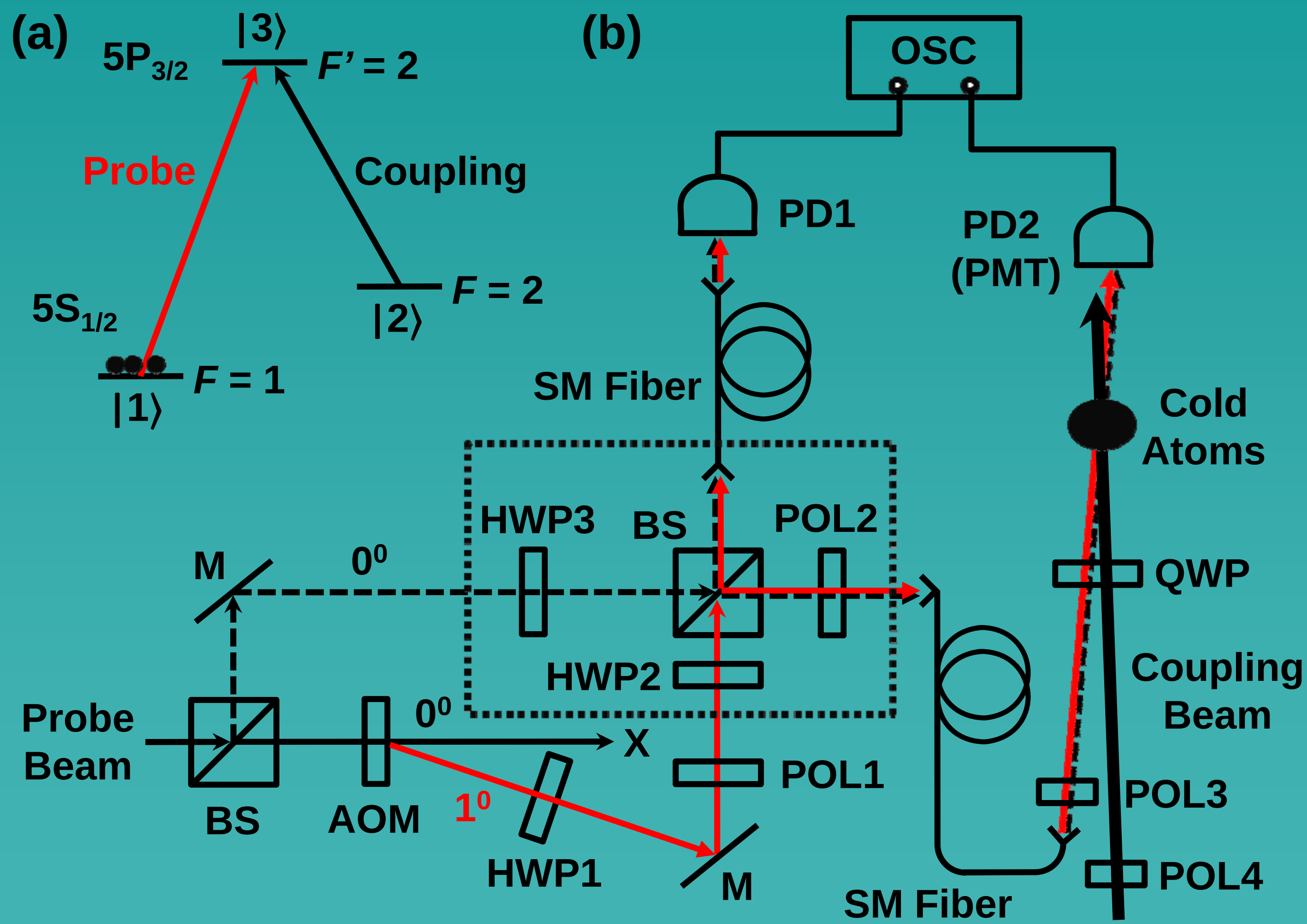


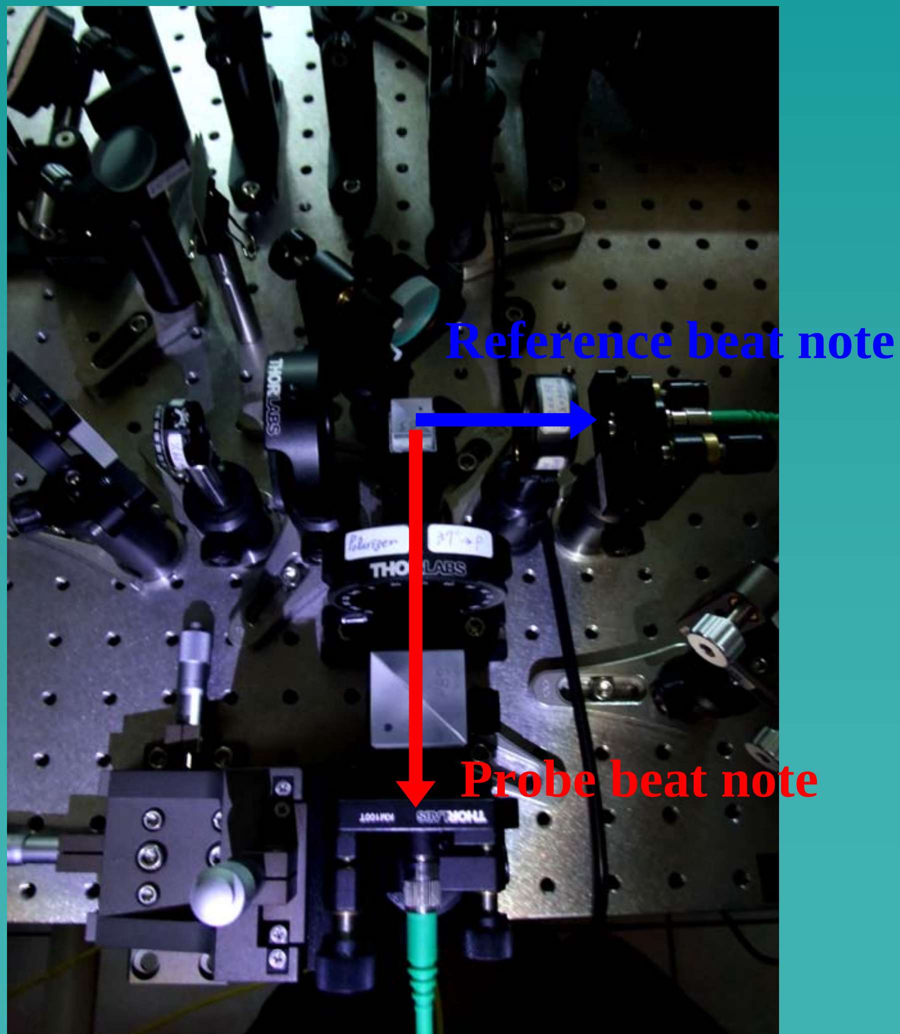

Phase measurement of weak probe pulses with peak power **~ 400 pW**

Phys. Rev. A **72**, 033812 (2005)

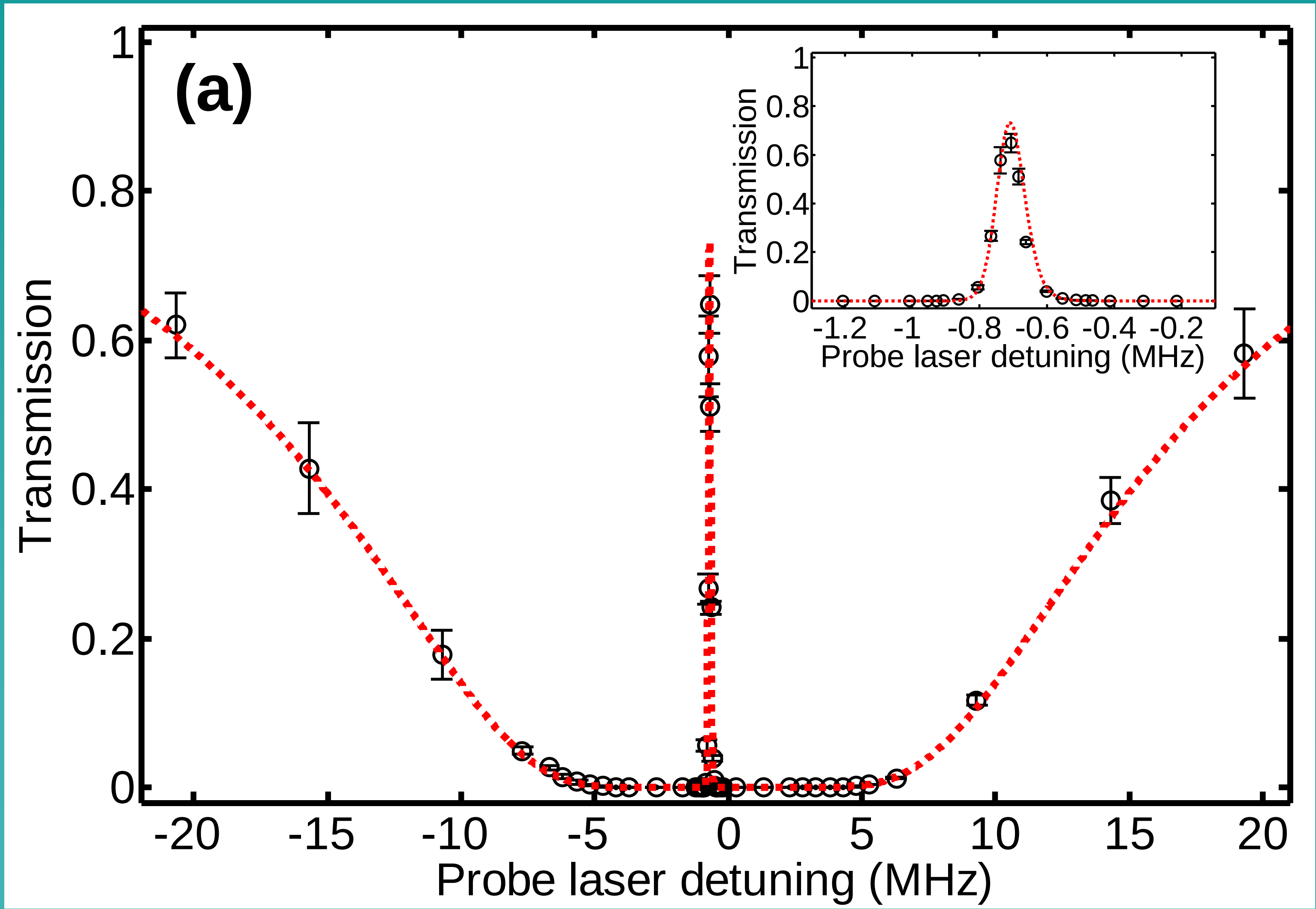
# Ultralow-light-level Beat-note Interferometer



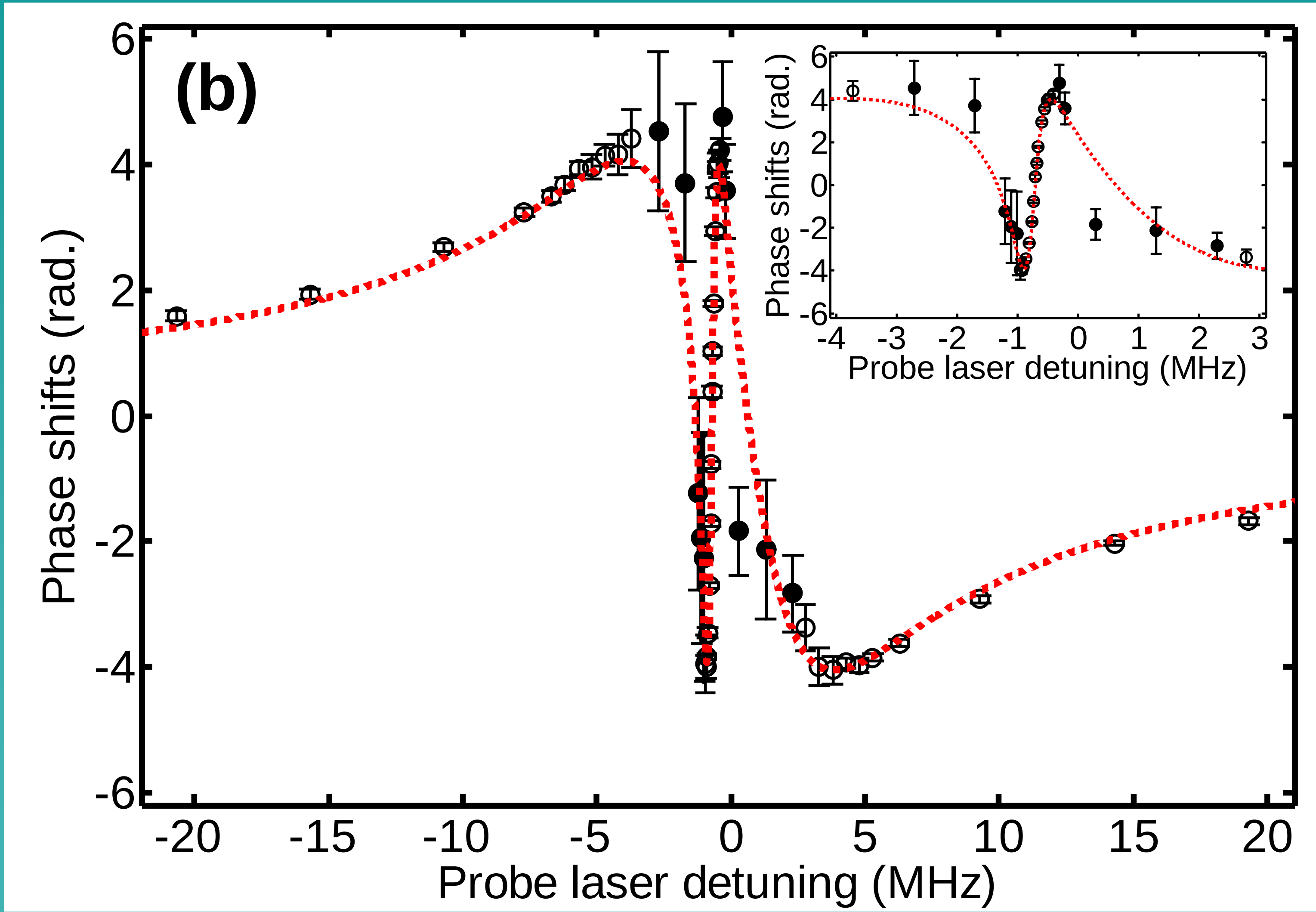
# Ultralow-light-level Beat-note Interferometer



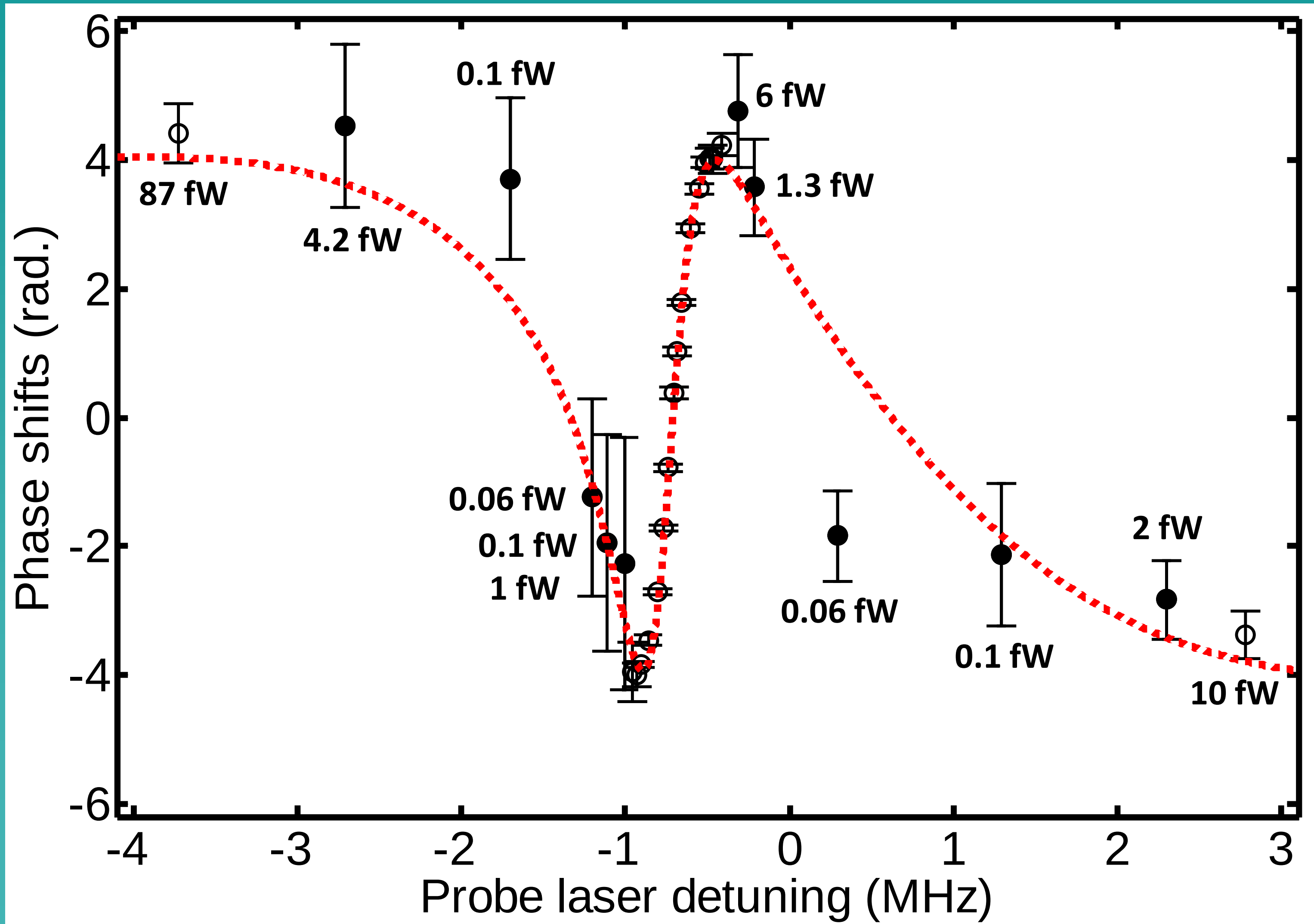
# EIT Transmission Spectrum by Beat-note Interferometer



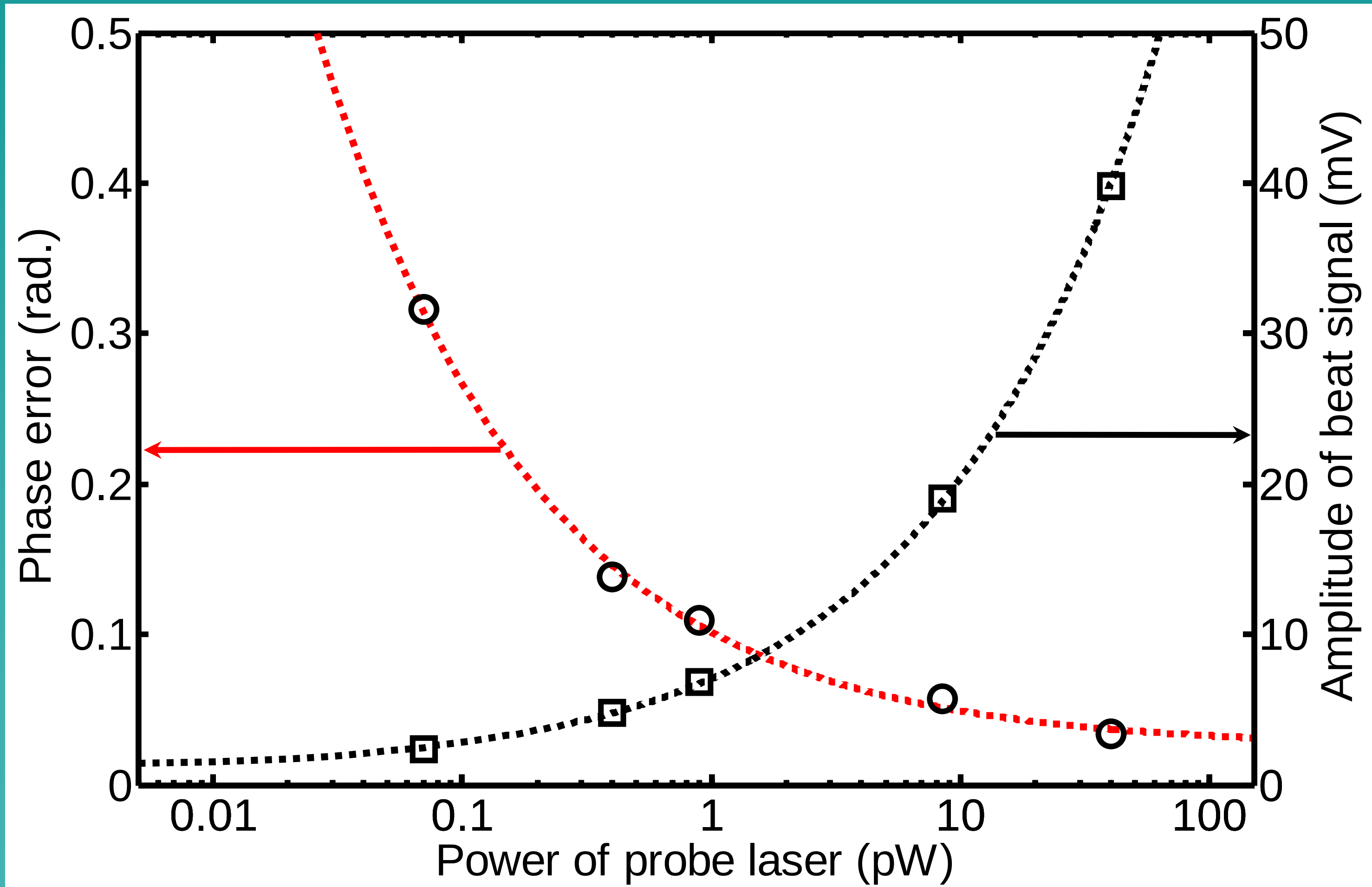
# EIT Phase Measurement at Ultralow Light Level



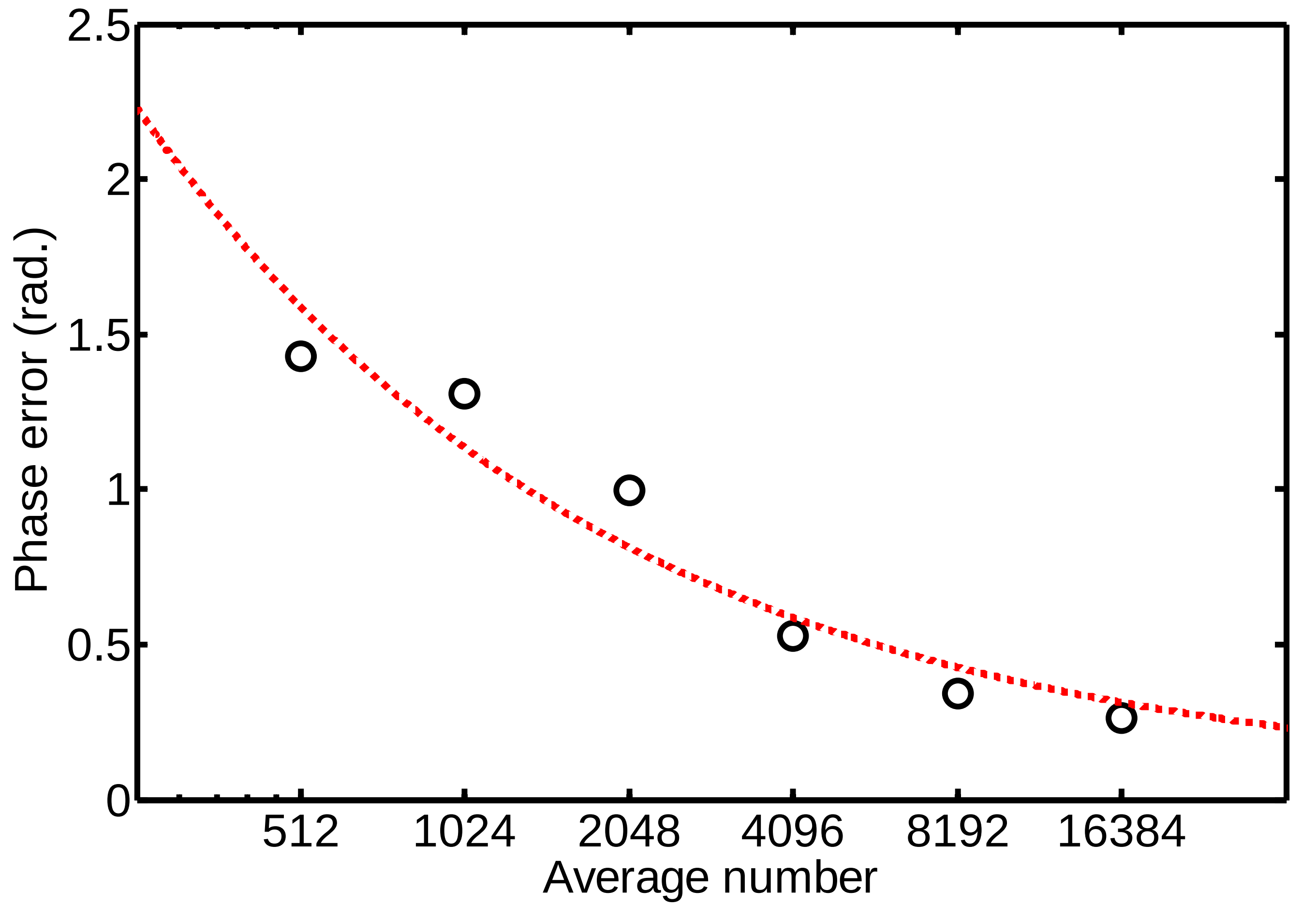
# EIT Phase Measurement at Atto-watt Light Level



# Amplitude and Phase Error of Beat Notes

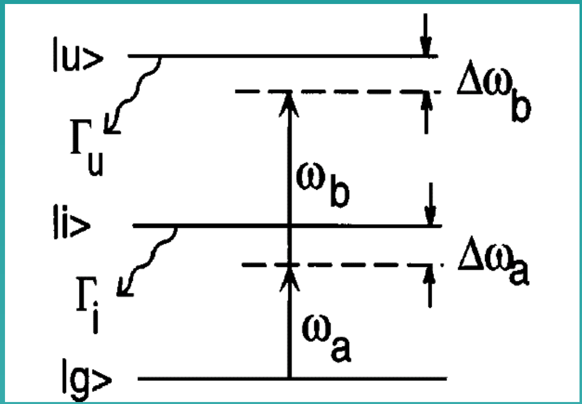


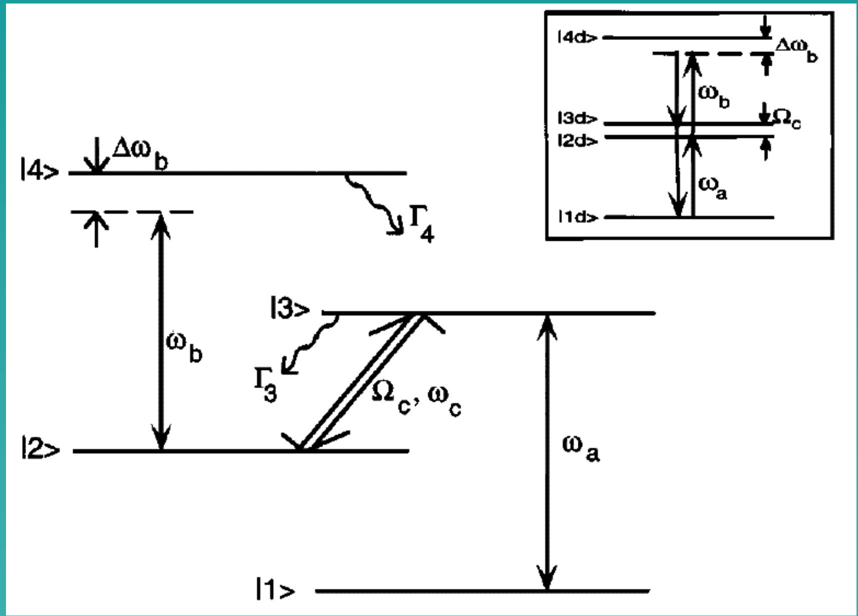
# Reduction of Phase Error



# Cross phase modulation (XPM) with EIT

# Giant Kerr Effect with EIT



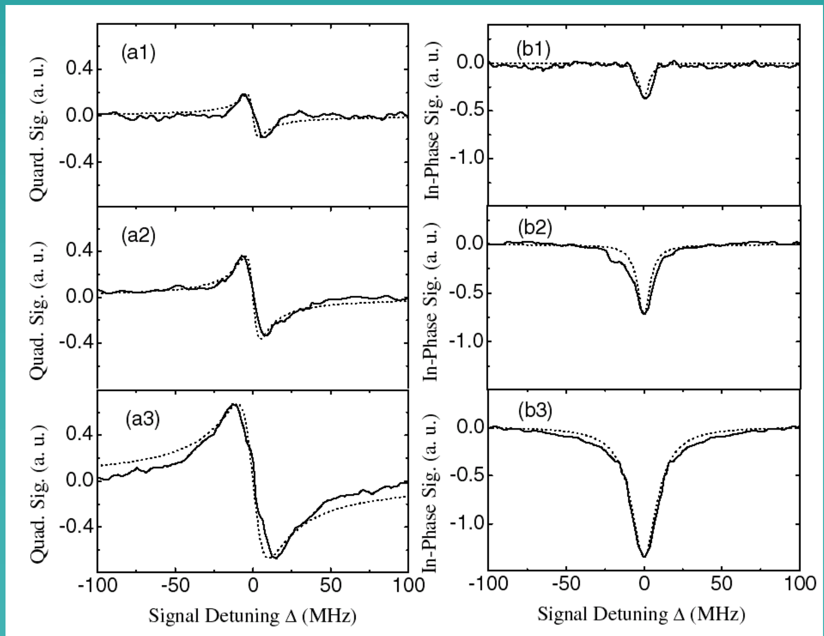

| | EIT Scheme | Three-Level Scheme |
|---|---|---|
| Loss | $\frac{N\|\mu_{13}\|^2\|\mu_{24}\|^2}{4\epsilon_0\hbar^3}\,\frac{\Gamma_4}{\Omega_c{}^2\Delta\omega_b{}^2}$ | $\frac{N\|\mu_{gi}\|^2\|}{\epsilon_0\hbar}\,\frac{\Gamma_i}{\Delta\omega_a{}^2}$ |
| Re[$\chi^{(3)}$] | $\frac{N\|\mu_{13}\|^2\|\mu_{24}\|^2}{2\epsilon_0\hbar^3}\,\frac{\Gamma_4}{\Omega_c{}^2\Delta\omega_b}$ | $\frac{N\|\mu_{gi}\|^2\|\mu_{iu}\|^2}{8\epsilon_0\hbar^3}\,\frac{1}{\Delta\omega_a{}^2\Delta\omega_b}$ |
| $\Phi_{\mathrm{XPM}}/(\alpha L)$ | $\sim\frac{\Delta\omega_b}{\Gamma_4}$ | $\sim\frac{\|\mu_{iu}\|^2}{\Gamma_i\Delta\omega_b}\|E_b\|^2$ |

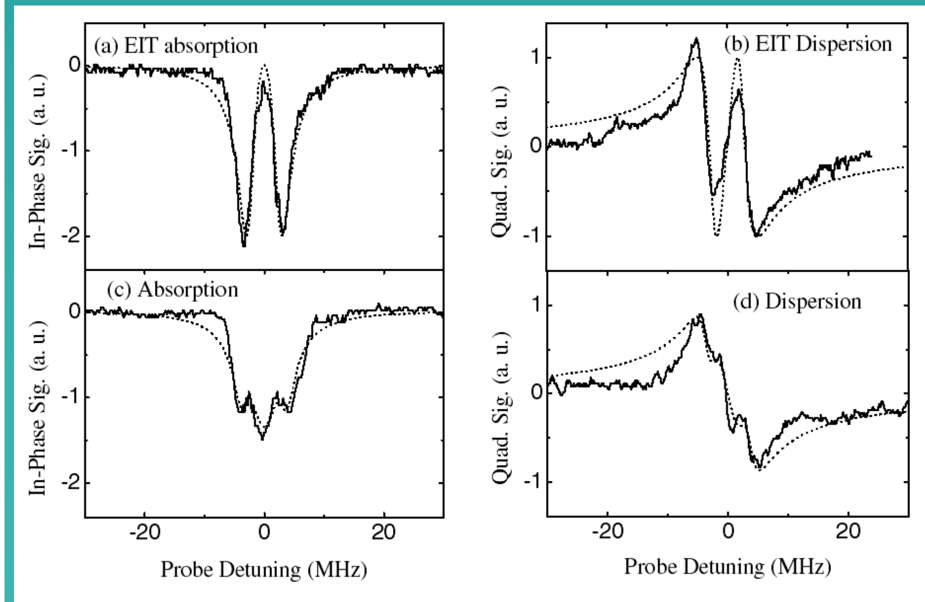
H. Schmidt and A. Imamoğlu, *Opt. Lett.* **21**, 1936 (1996).

# Observation of Large Kerr Nonlinearity at Low Light Intensities

Hoonsoo Kang and Yifu Zhu
*Department of Physics, Florida International University, Miami, Florida 33199, USA*
(Received 6 March 2003; published 26 August 2003)

We report an experimental observation of large Kerr nonlinearity with vanishing linear susceptibilities in coherently prepared four-level rubidium atoms. Quantum coherence and interference manifested by electromagnetically induced transparency suppress the linear susceptibilities and greatly enhance the nonlinear susceptibilities at low light intensities. The measured Kerr nonlinearity is comparable in magnitude to the linear dispersion in a simple two-level system and is several orders of magnitude greater than the Kerr nonlinearity of a conventional three-level scheme under similar conditions.

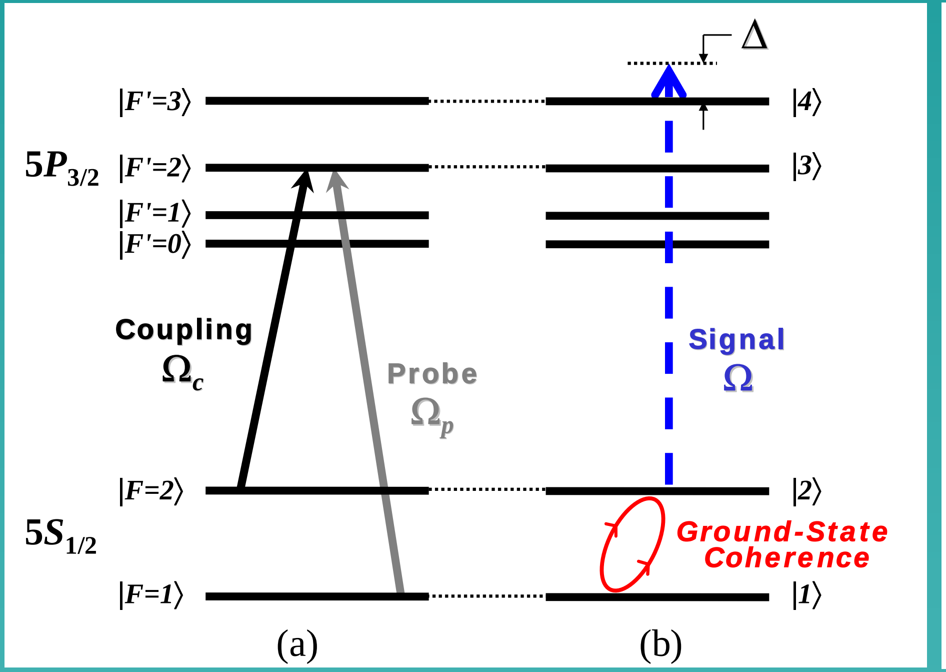


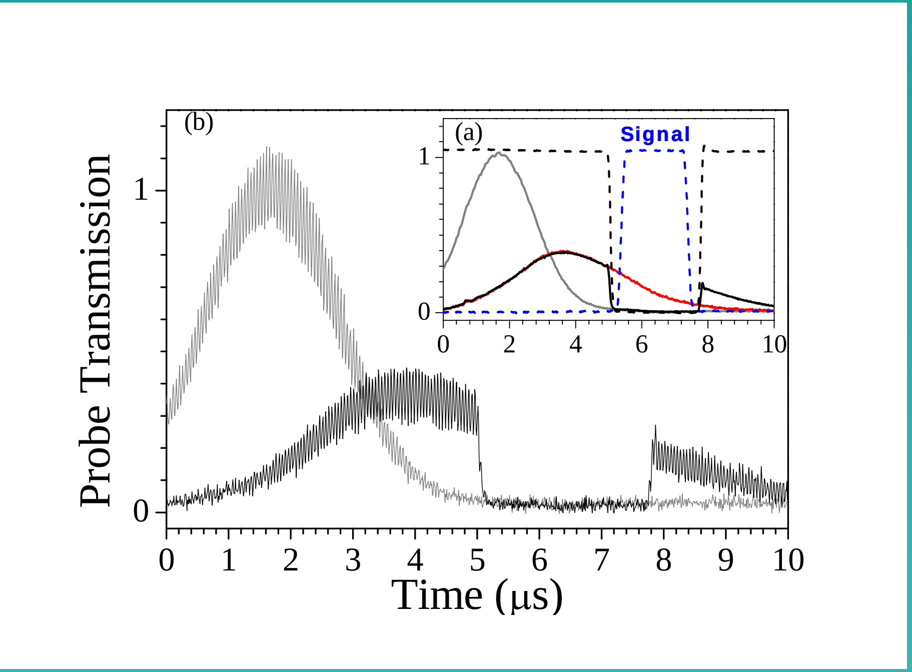




$I_s$ ~ 1 mW/cm$^2$ ⟹ $\Phi$~ 0.2 radians

H. Kang and Y. Zhu, *Phys. Rev. Lett.* **91**, 093601 (2003).

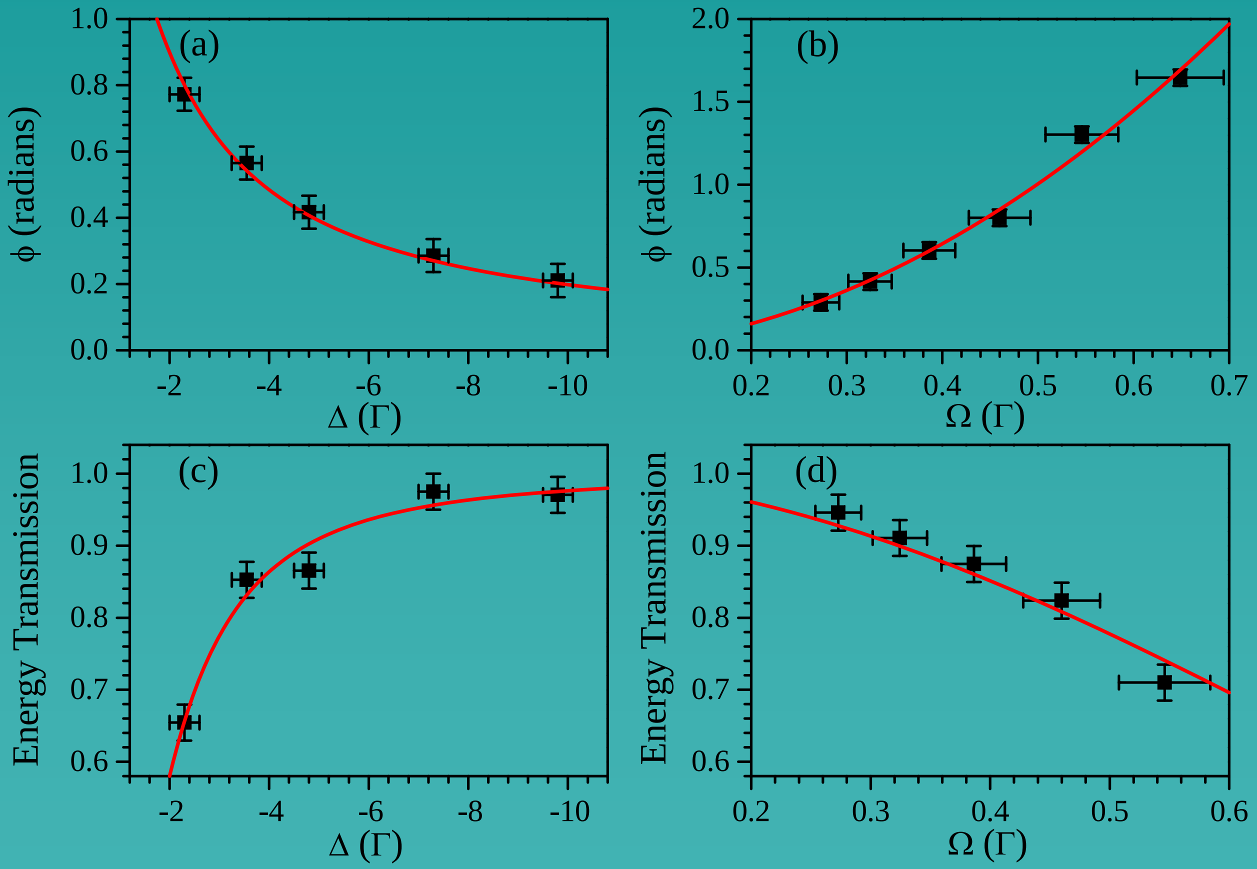
# Light storage Cross-Phase Modulation (XPM) Scheme




PRL **96**, 043603 (2006)

# Light storage Cross-Phase Modulation (XPM) Scheme




$$\phi = \frac{\Omega^2 \Delta}{\Gamma^2 + 4\Delta^2}\tau$$

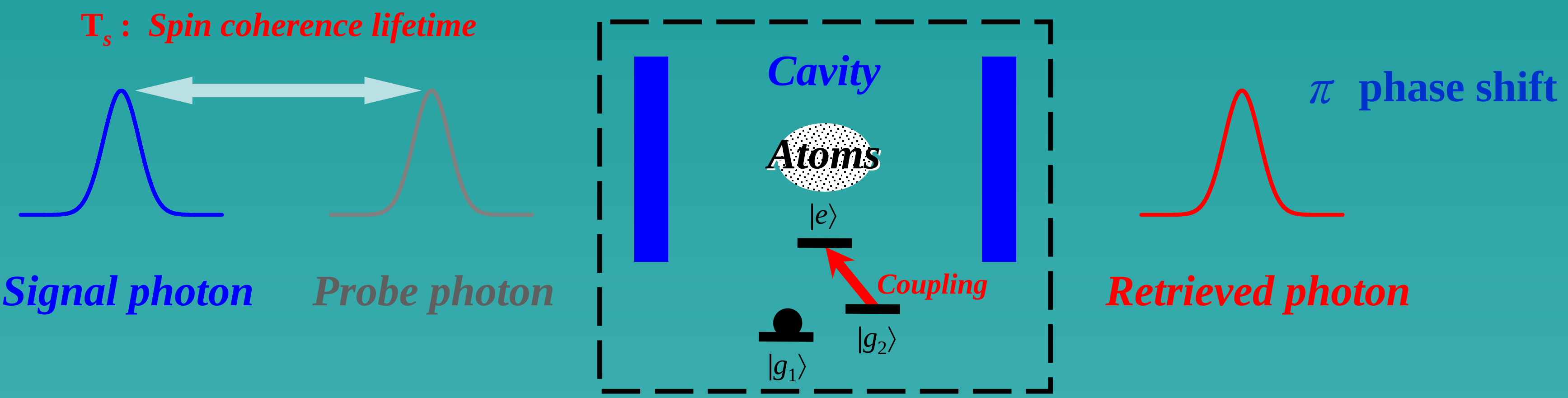
$$\alpha = \frac{\Omega^2 \Delta}{\Gamma^2 + 4\Delta^2}\tau$$

$$\Rightarrow \frac{\phi}{\alpha} = \frac{\Delta}{\Gamma}$$

**$I_s$ ~ 1 mW/cm$^2$** ⇨ **Φ~ 1.0 radians**

PRL **96**, 043603 (2006)

# Cavity EIT : Single-photon $\pi$-phase gate ?




Single-photon $\pi$-phase gate may be possible !
But still need more efforts !!!

nature photonics

LETTERS

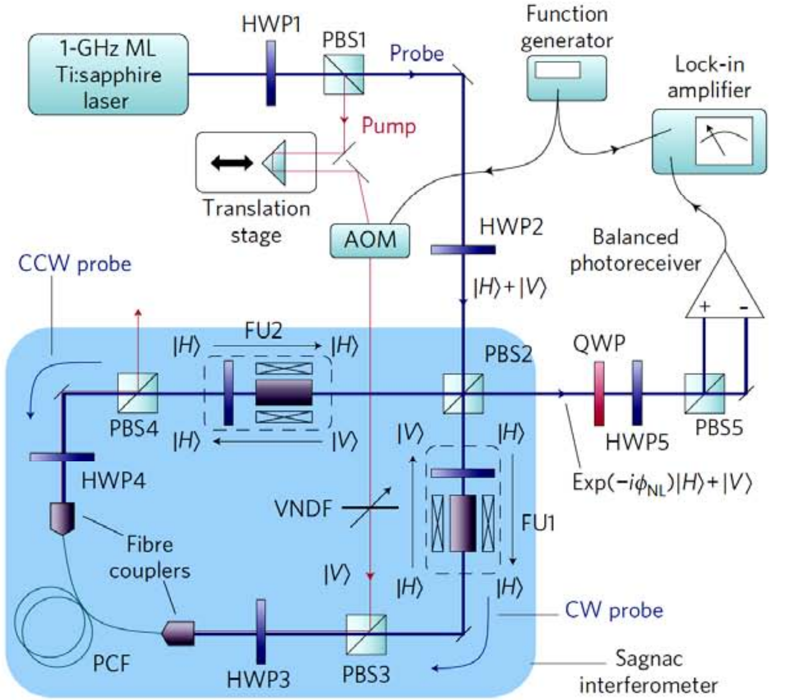
PUBLISHED ONLINE: 25 JANUARY 2009 | DOI: 10.1038/NPHOTON.2008.292

# Observation of optical-fibre Kerr nonlinearity at the single-photon level

Nobuyuki Matsuda[1,2]*, Ryosuke Shimizu[2,3], Yasuyoshi Mitsumori[1,2], Hideo Kosaka[1,2] and Keiichi Edamatsu[1,2]

**Optical fibres have proved to be an important medium for manipulating and generating light in applications including soliton transmission[1], light amplification[2], all-optical switching[3] and supercontinuum generation[4]. In the quantum regime, fibres may prove useful for ultralow-power all-optical signal processing[5] and quantum information processing[6]. Here, we demonstrate the first experimental observation of optical nonlinearity at the single-photon level in an optical fibre. Taking advantage of the large nonlinearity and managed dispersion of photonic crystal fibres[7,8], we report very small ($1 \times 10^{-7}$ to $\sim 1 \times 10^{-8}$ rad) conditional phase shifts induced by weak coherent pulses that contain one or less than one photon per pulse on average. We discuss the feasibility of quantum information processing using optical fibres, taking into account the observed Kerr nonlinearity, accompanied by ultrafast response time and low induced loss.**

The photon, the quantum unit of light, has much less interaction with its environment than other quanta (for example, electron spin, superconducting current) and for this reason it is an outstanding carrier of information in quantum communication and has earned the name the 'flying qubit'. This lack of interaction also means that photons may not be suitable for computations that




Nobuyuki Matsuda *et al.*, Nat. Photonics **3**, 95 (2009).

# Summary & Outlook

- ✓ Toward single photon generation with atomic ensembles
- ✓ Ultralow-light-level phase measurement by beat-note interferometer
- ✓ Study EIT-based XPM at low-light level

# Acknowledgement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Ite A. Yu's group (NTHU)

Ying-Cheng Chen's group (IAMS)

Yueh-Nan Chen (NCKU)