Ultra-Slow (and Superluminal) Light Propagation in Room Temperature Solids

Robert W. Boyd

The Institute of Optics and
Department of Physics and Astronomy
University of Rochester, Rochester, NY 14627
http://www.optics.rochester.edu

Presented at the Physics of Quantum Electronics, Snowbird, Utah, January 7, 2004.

PQE -- 2004
Slow Light, Superluminal Light, and their Applications

Tuesday Evening

20:50 **Daniel J. Gauthier** ,*Duke University*
The information velocity in fast- and slow-light media

21:10 **Lijun Wang** ,*NEC*
Quantum fluctuation, causality, and Abraham force

21:30 **George R. Welch** ,*Texas A&M University*
Buffer-gas induced absorption resonances and large negative pulse delay times in Rb vapor

21:50 **Andrey Matsko** ,*Jet Propulsion Laboratory*
EIT in resonator chains: similarities and differences with atomic media

Wednesday Morning

8:40 **Kurt E. Oughstun** ,*University of Vermont*
Accuracy of the Group Velocity Description and the Question of Superluminal Pulse Velocities

9:00 **Dmitry Strekalov** ,*Jet Propulsion Laboratory*
Influence of inhomogeneous broadening on group velocity in coherently pumped atomic vapor

9:20 **Vladimir M. Shalaev** ,*Purdue University*
Plasmonic Nanoantennae for Manipulating Light, Sensing Molecules, and Nanomanufacturing

9:50 **John Howell** ,*University of Rochester*
Pixel entanglement: position-momentum quantum information processing

Causality and Superluminality

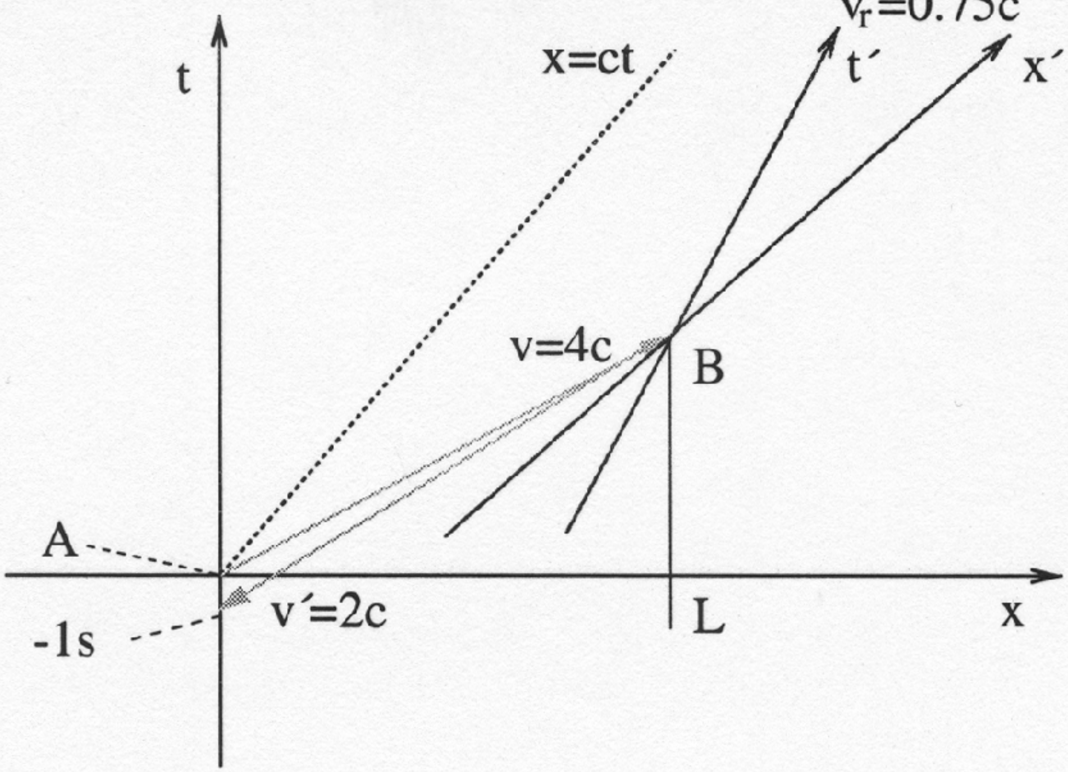


Fig. 6 Coordinates of two inertial observers **A** $(0,0)$ and **B** with $O(x,t)$ and $O'(x',t')$ moving with a relative velocity of $0.75c$. The distance L between **A** and **B** is 2000000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v'_s = 2c$. The numbers in the example are chosen arbitrarily. The signal returns −1 s in the past in **A**.

Ann. Phys. (Leipzig) 11, 2002.

Interest in Slow Light

Intrigue: Can (group) refractive index really be 10^6?

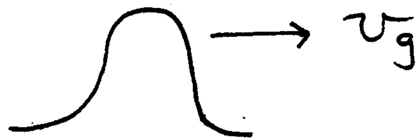
Fundamentals of optical physics

Optical delay lines, optical storage, optical memories

Implications for quantum information

Group Velocity

Pulse
(wave packet)



Group velocity given by $v_g = \frac{d\omega}{dk}$

For $k = \frac{n\omega}{c}$. $\frac{dk}{d\omega} = \frac{1}{c}\left(n + \omega \frac{dn}{d\omega}\right)$

Thus

$$v_g = \frac{c}{n + \omega \frac{dn}{d\omega}} \equiv \frac{c}{n_g}$$

Thus $n_g \neq n$ in a dispersive medium!

Slow Light in Atomic Vapors

Slow light propagation in atomic vapors, facilitated by quantum coherence effects (EIT, CPO), has been successfully observed by

Hau and Harris

Welch and Scully

Budker

and others

Challenge/Goal

Slow light in room-temperature solid-state material.

- Slow light in room temperature ruby
  (facilitated by a novel quantum coherence effect)
- Slow light in a structured waveguide

Slow Light in Ruby

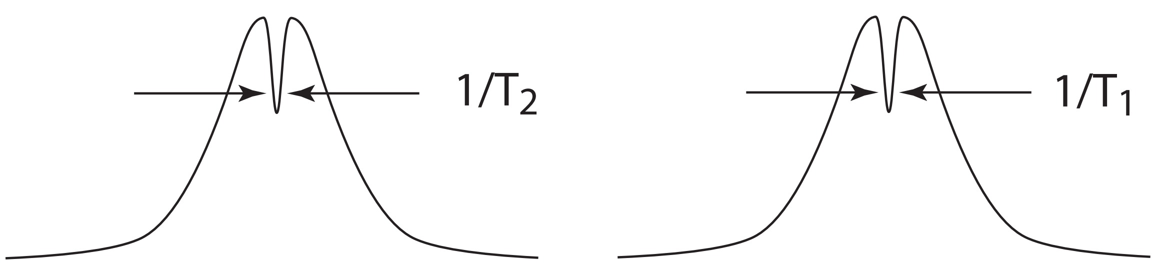
Need a large dn/dω. (How?)

Kramers-Kronig relations:
Want a very narrow absorption line.

Well-known (to the few people how know it well) how to do so:

Make use of “spectral holes” due to population oscillations.

Hole-burning in a homogeneously broadened line; requires $T_2 << T_1$.

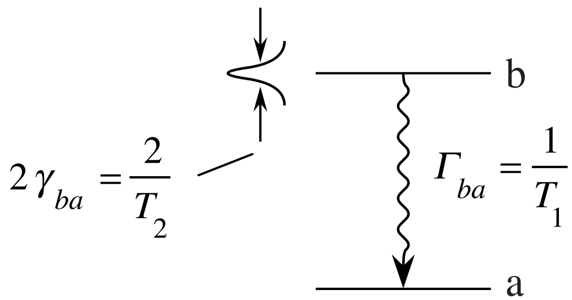


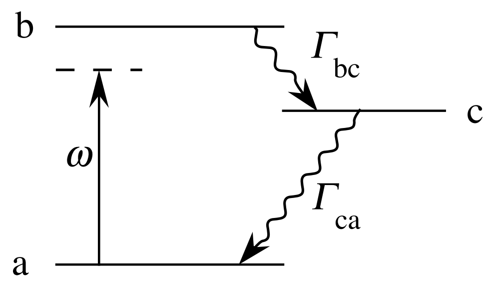
inhomogeneously broadened medium

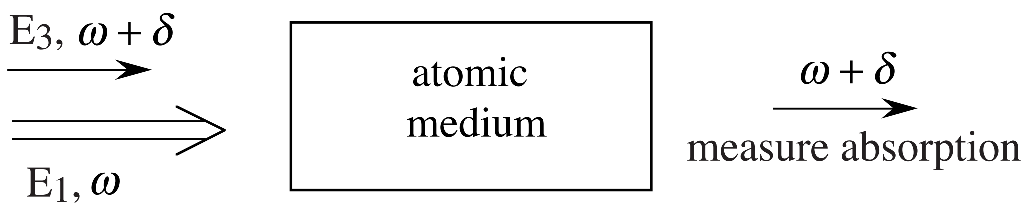
homogeneously broadened medium (or inhomogeneously broadened)

PRL 90,113903(2003); see also news story in Nature.

Spectral Holes Due to Population Oscillations







Population inversion:

$$(\rho_{bb} - \rho_{aa}) = w \qquad w(t) \approx w^{(0)} + w^{(-\delta)} e^{i\delta t} + w^{(\delta)} e^{-i\delta t}$$

population oscillation terms important only for $\delta \leq 1/T_1$

Probe-beam response:

$$\rho_{ba}(\omega+\delta) = \frac{\mu_{ba}}{\hbar} \frac{1}{\omega - \omega_{ba} + i/T_2} \left[E_3 w^{(0)} + E_1 w^{(\delta)} \right]$$

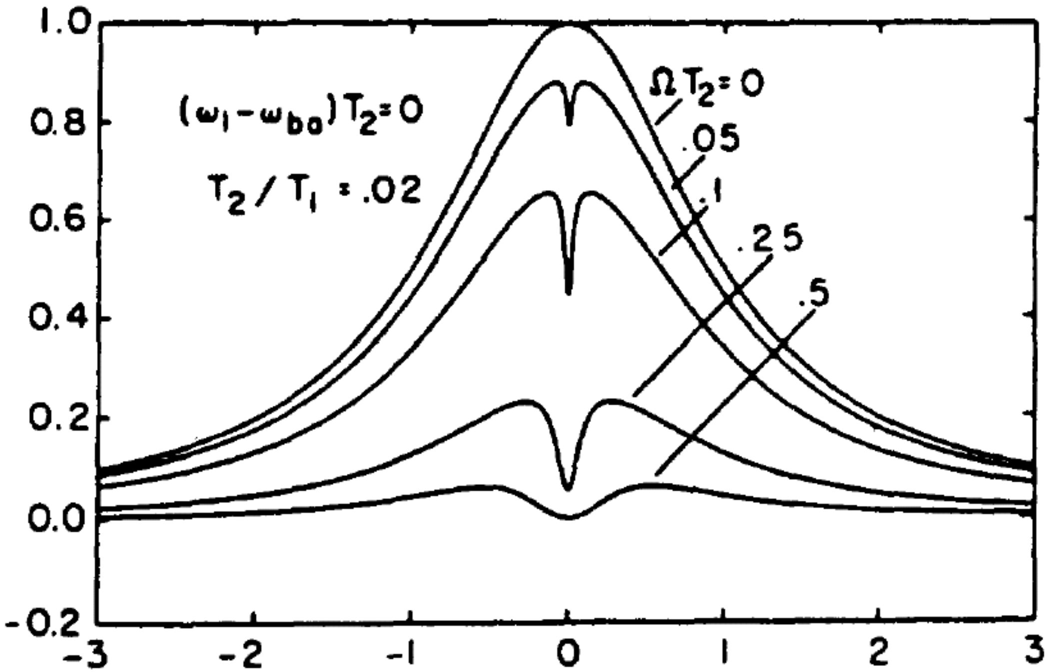
Probe-beam absorption:

$$\alpha(\omega+\delta)\, \mu \left[w^{(0)} - \frac{\Omega^2 T_2}{T_1} \frac{1}{\delta^2 + \beta^2} \right]$$

linewidth $\quad \beta = (1/T_1)(1 + \Omega^2 T_1 T_2)$

Spectral Holes in Homogeneously Broadened Materials

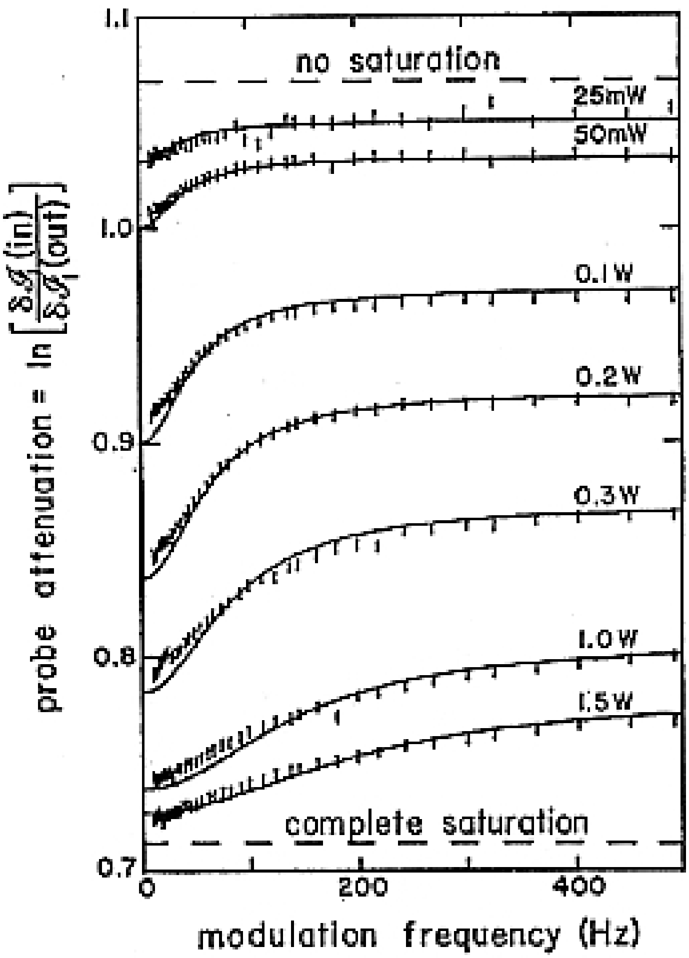
Occurs only in collisionally broadened media ($T_2 << T_1$)



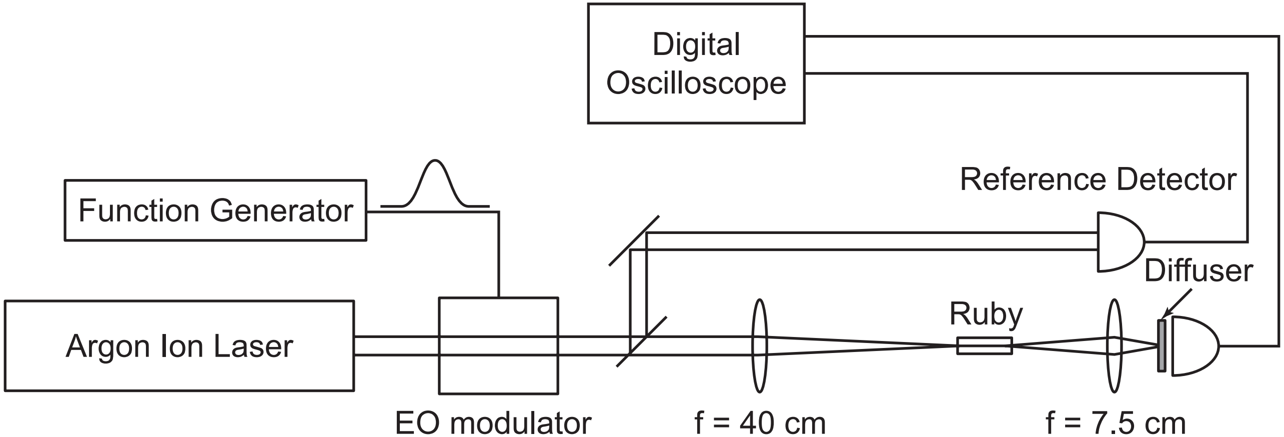
Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

OBSERVATION OF A SPECTRAL HOLE DUE TO POPULATION OSCILLATIONS IN A HOMOGENEOUSLY BROADENED OPTICAL ABSORPTION LINE

Lloyd W. HILLMAN, Robert W. BOYD, Jerzy KRASINSKI and C.R. STROUD, Jr.
The Institute of Optics, University of Rochester, Rochester, NY 14627, USA

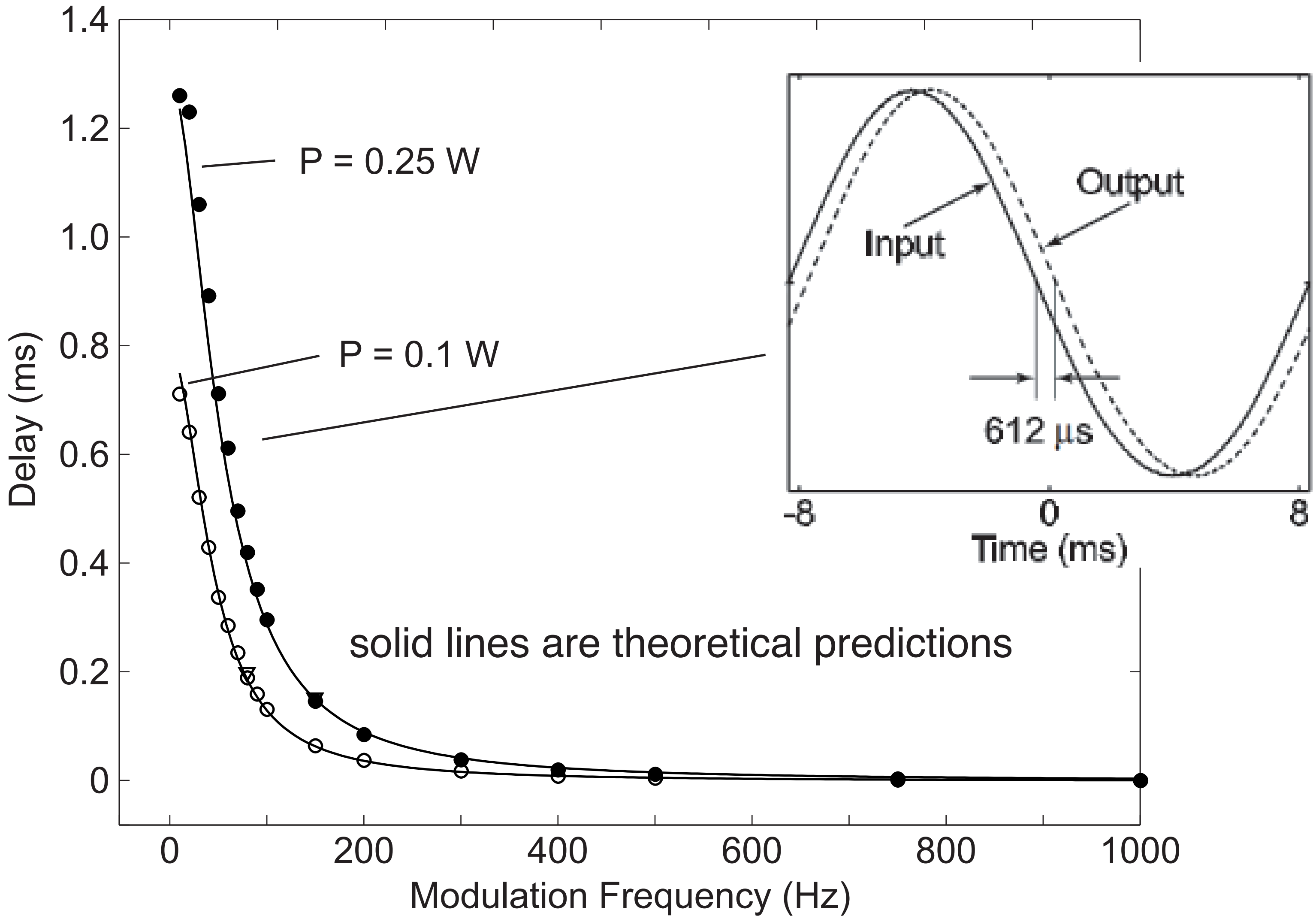


Experimental Setup Used to Observe Slow Light in Ruby



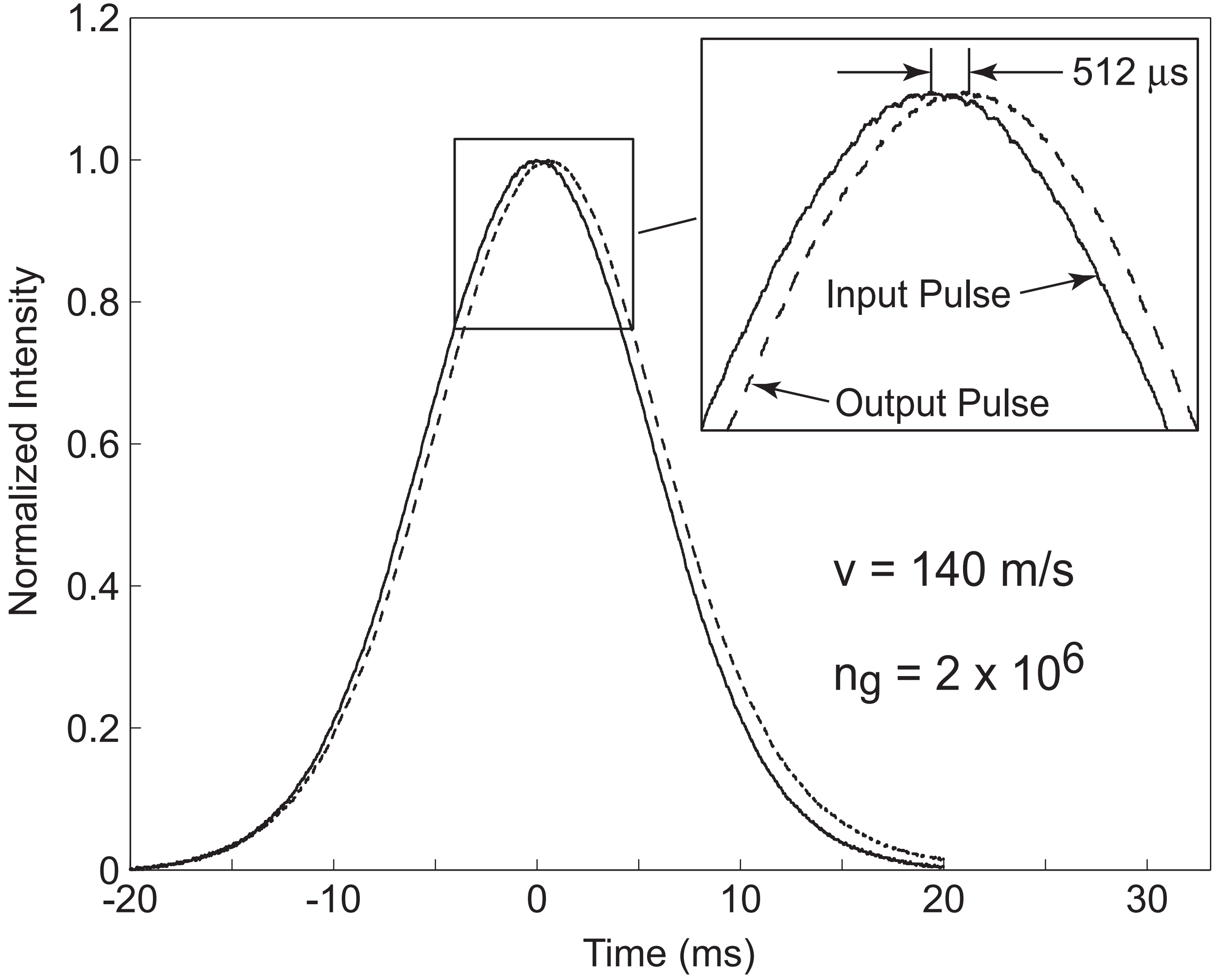
7.25 cm ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



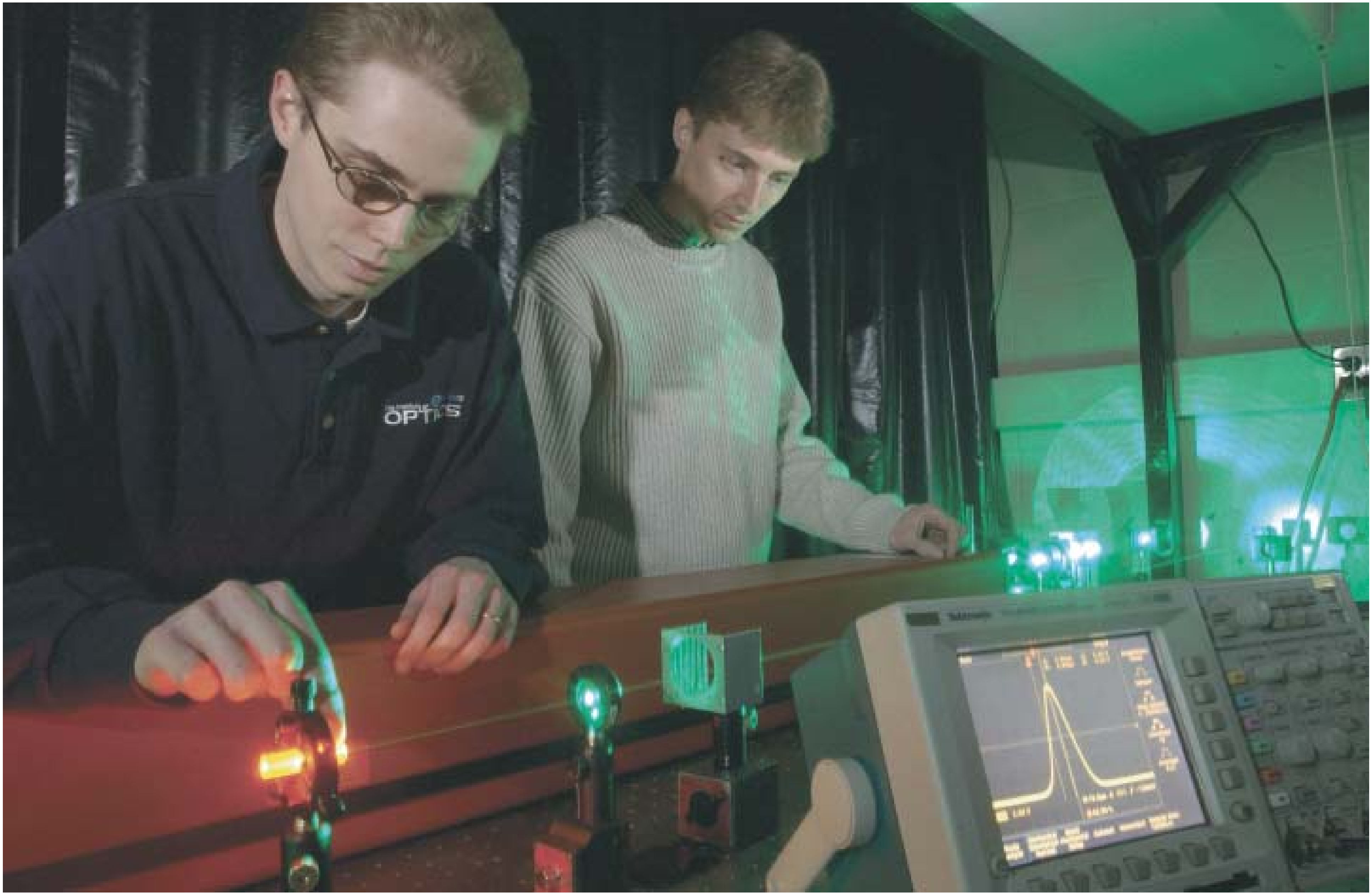
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

Gaussian Pulse Propagation Through Ruby

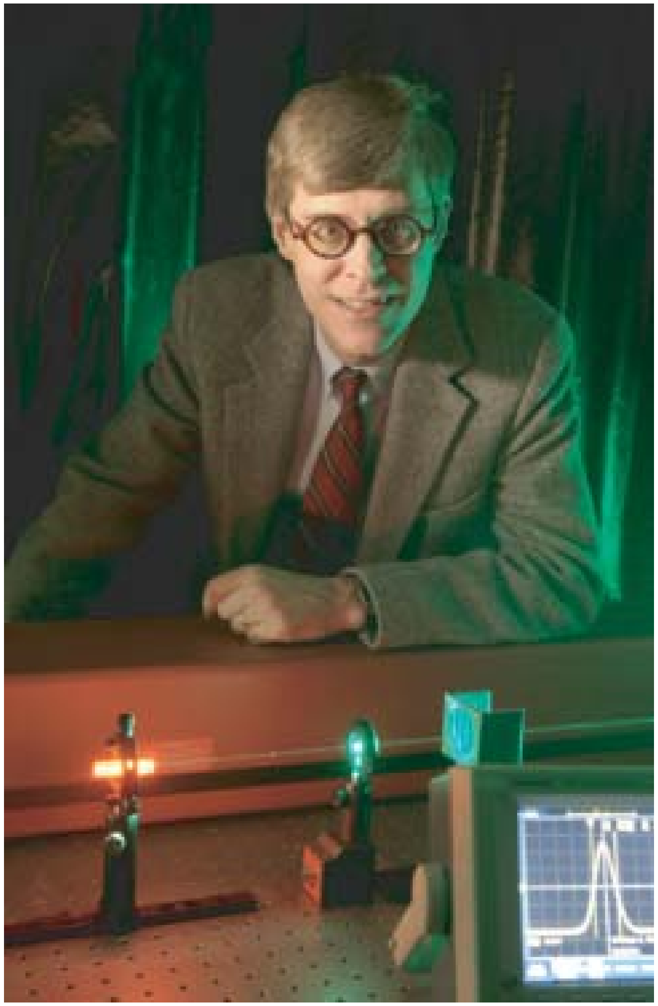


No pulse distortion!

Matt Bigelow and Nick Lepeshkin in the Lab



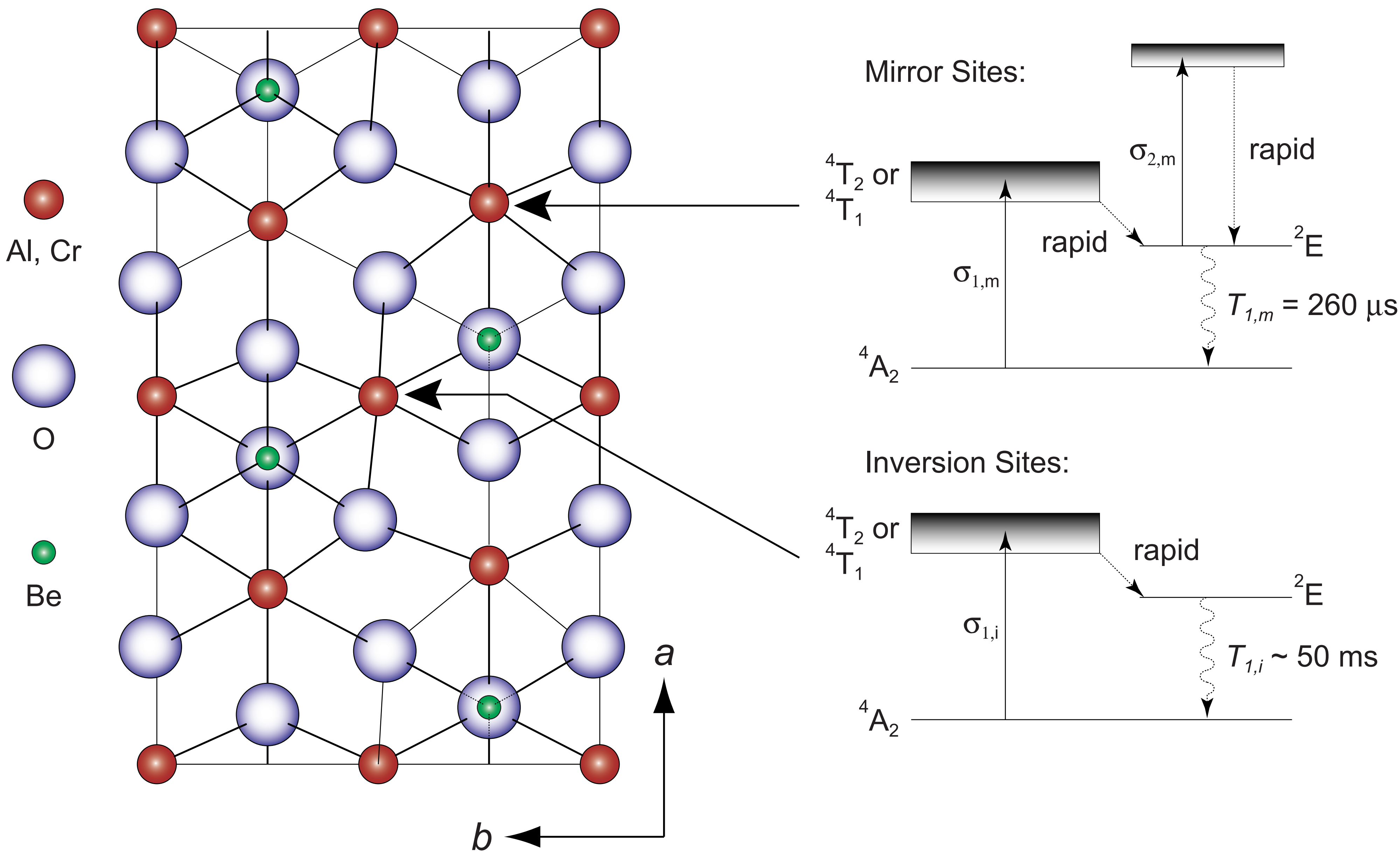
Comparison of University of Rochester and University of Arizona



Bob and Ruby

Hyatt and Galina

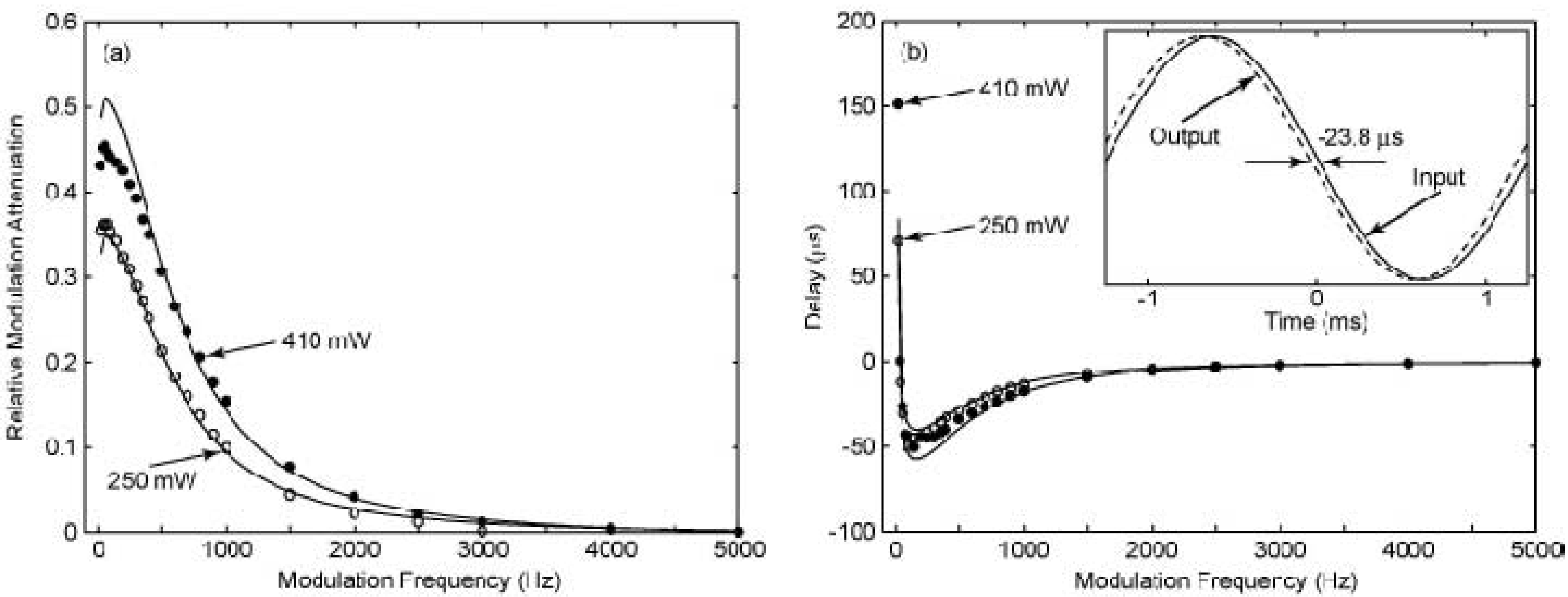
Alexandrite Displays both Saturable and Inverse-Saturable Absorption



Inverse-Saturable Absorption Produces Superluminal Propagation in Alexandrite

At 476 nm, alexandrite is an inverse saturable absorber

Negative time delay of 50 μs correponds to a velocity of -800 m/s



M. Bigelow, N. Lepeshkin, and RWB, Science, 2003

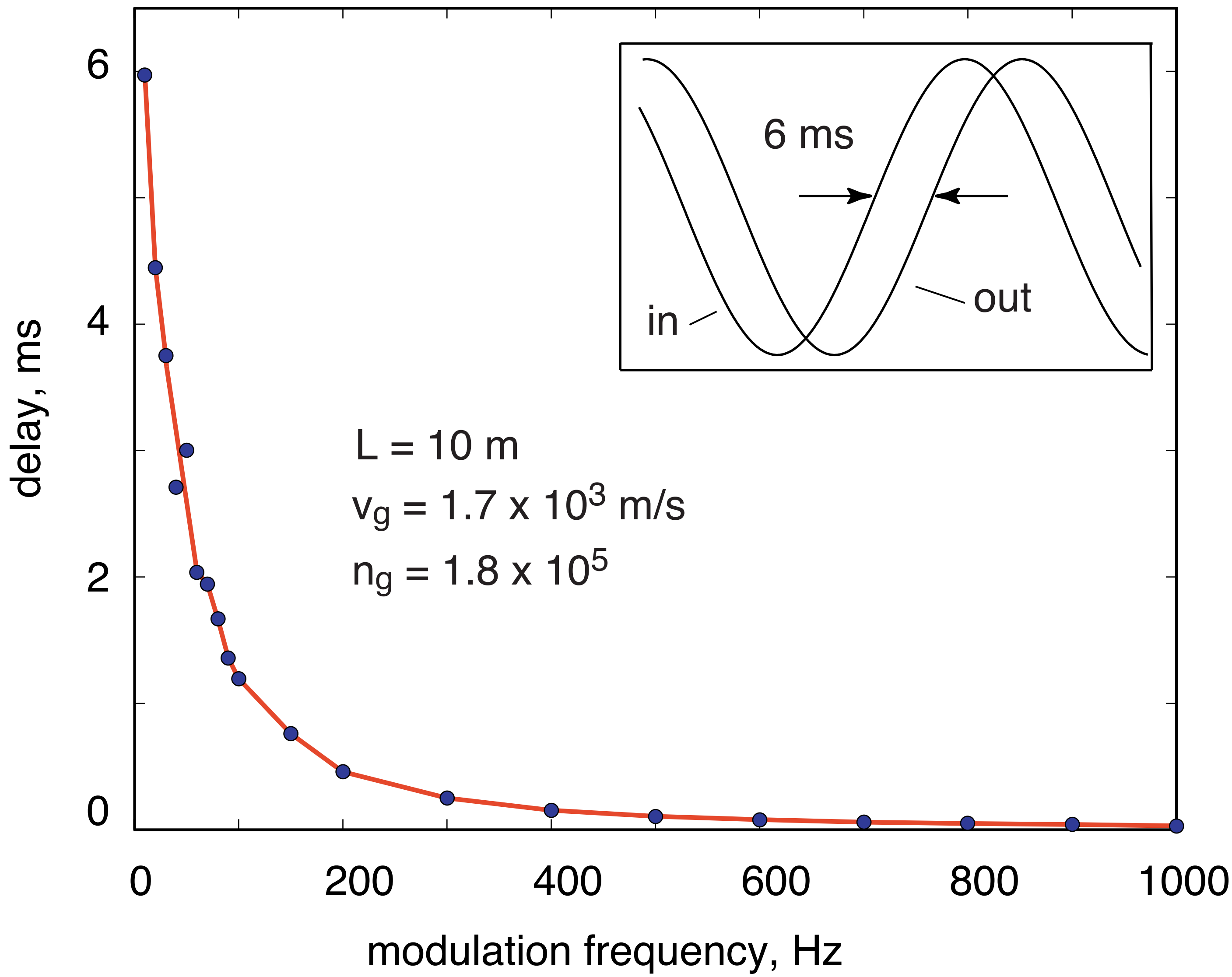
Slow and Fast Light --What Next?

Longer fractional delay
(saturate deeper; propagate farther)

Find material with faster response
(technique works with shorter pulses)

Produce slow light in optical waveguides
(to enable new applications)

Slow Light in an Erbium-Doped Fiber Amplifier



with S. Jarabo, University of Zaragoza

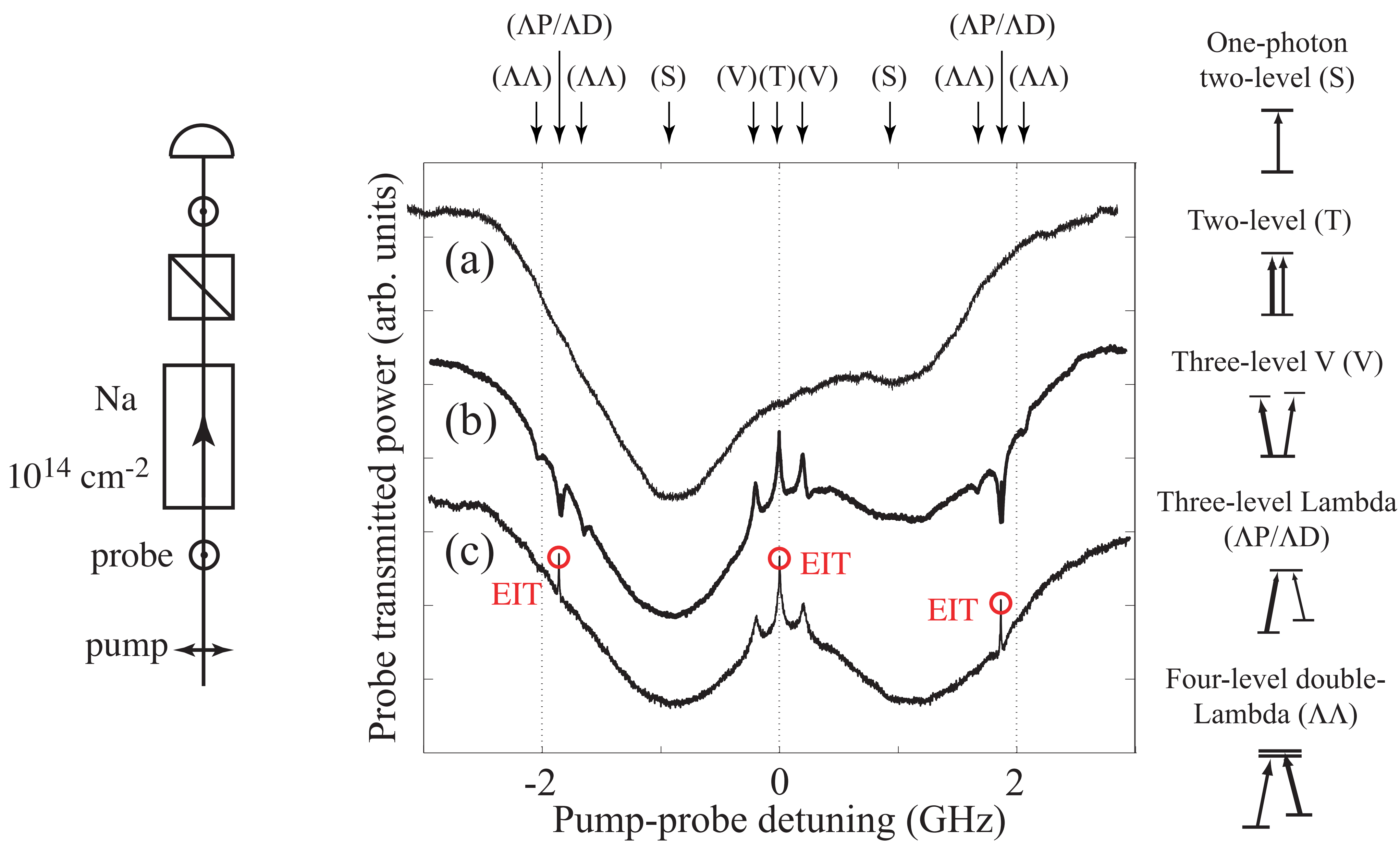
Implications of "Slow" Light

1. Controllable optical delay lines
   (a) Large total delay versus large fractional delay
   (b) True time delay for synthetic aperture radar
   (c) Buffers for optical processors and routers
2. New interactions enabled by slow light (e.g., SBS)
3. New possibilities with other materials
   (a) Semiconductor (bulk and heterostructures)
   (b) Laser dyes (gain, Q-switch, mode-lock)
   (c) rare-earth doped solids, especially EDFA's
4. How weak a signal can be used with these method?
5. Relation between slowness and enhanced nonlinearity

Related Work: EIT

Resonance Structure of the Sodium D1 Line

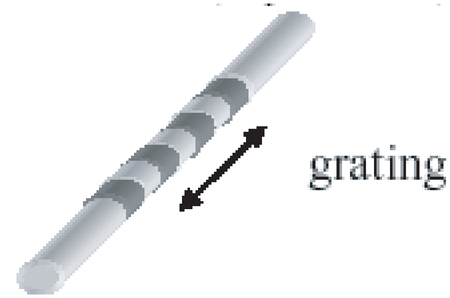
13 Pump-Probe Resonances of the Na D1 Line



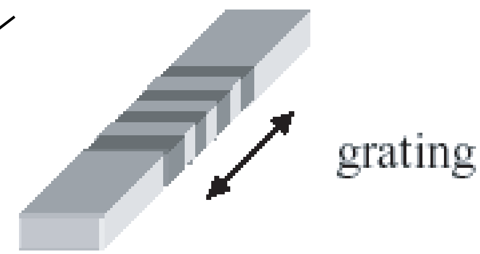
Wong et al., Phys. Rev. A 68, 012502 (2003). F. Narducci, Tuesday 21:50

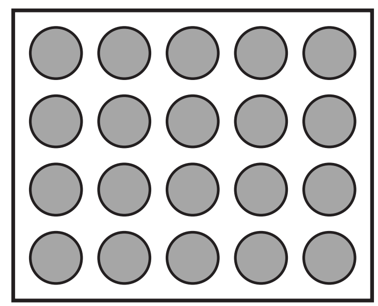
Artificial Materials for Nonlinear Optics

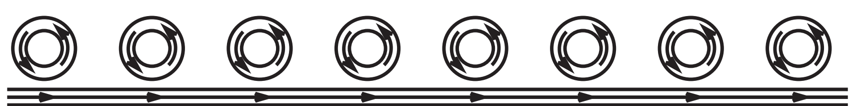
Artifical materials can produce
- Large nonlinear optical response
- Large dispersion and Slow light



Examples
- Fiber/waveguide Bragg gratings
- PBG materials
- CROW devices (Yariv, et al.)
- SCISSOR devices



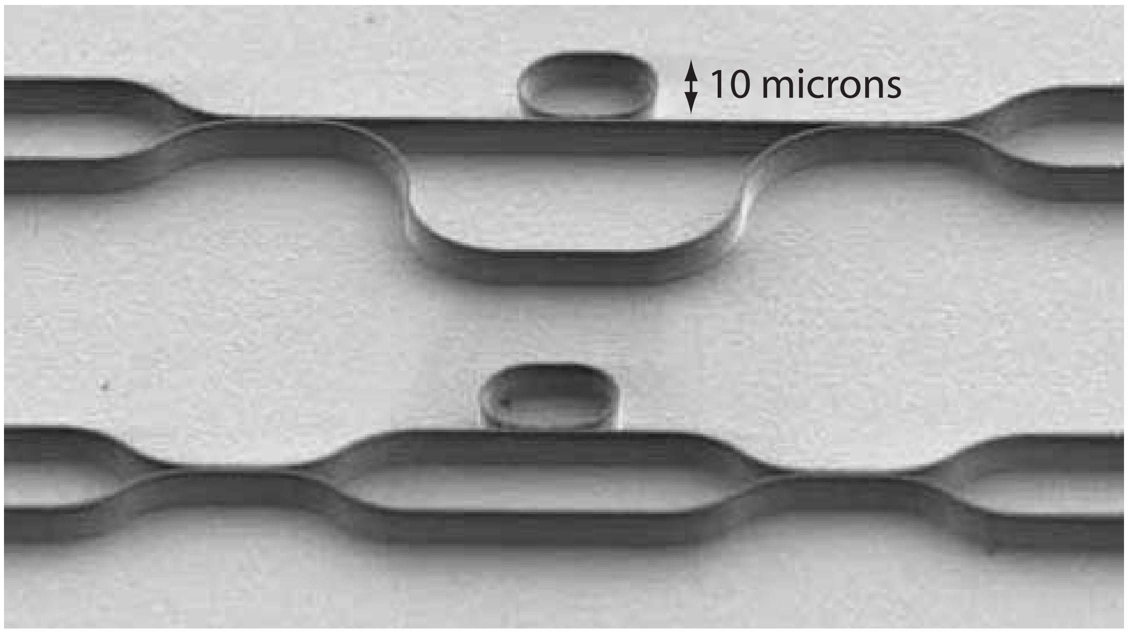




Note also talks in Tuesday Nanophotonics sessions

Microresonator-Based Photonic Devices

Resonator-Enhanced Mach-Zehnder Interferometers

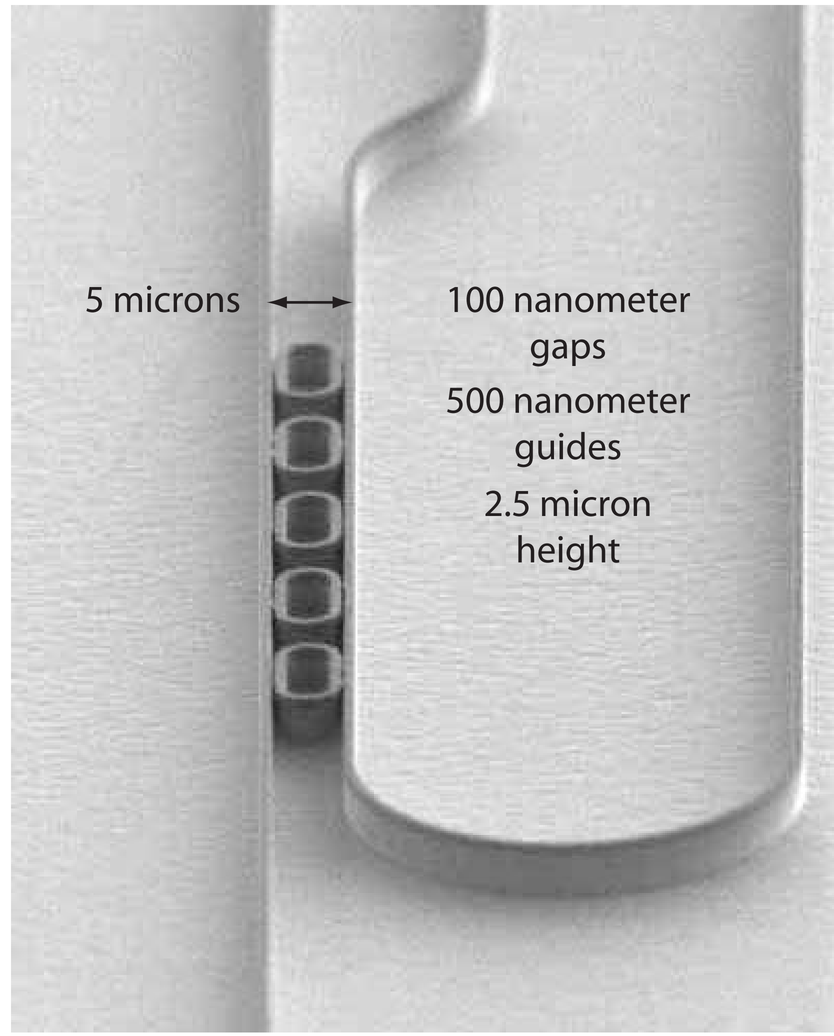


~100 nanometer gaps

500 nanometer guides

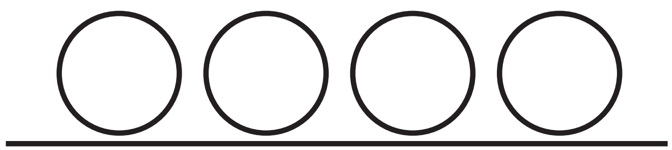
2.5 micron height

Five-Cell SCISSOR with Tap Channel

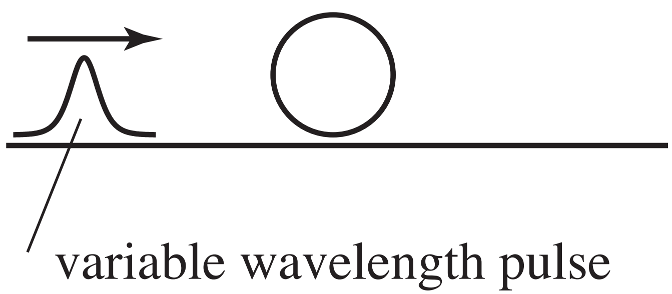


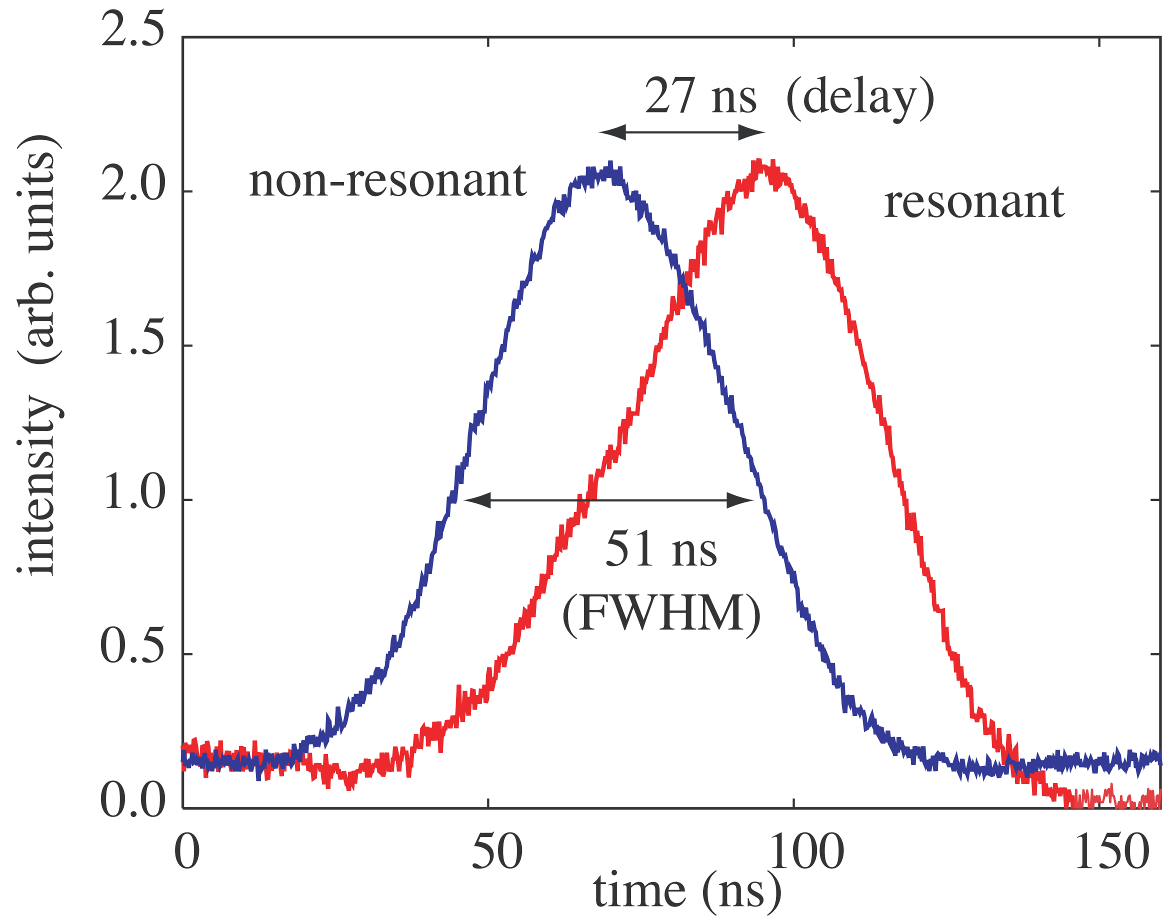
Fiber-Resonator Optical Delay Line

Fiber optical delay line:



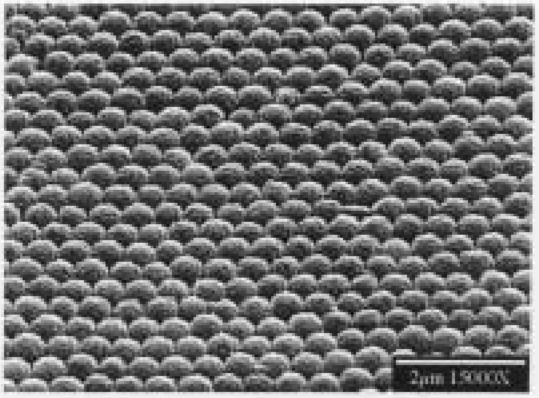
First study one element of optical delay line:





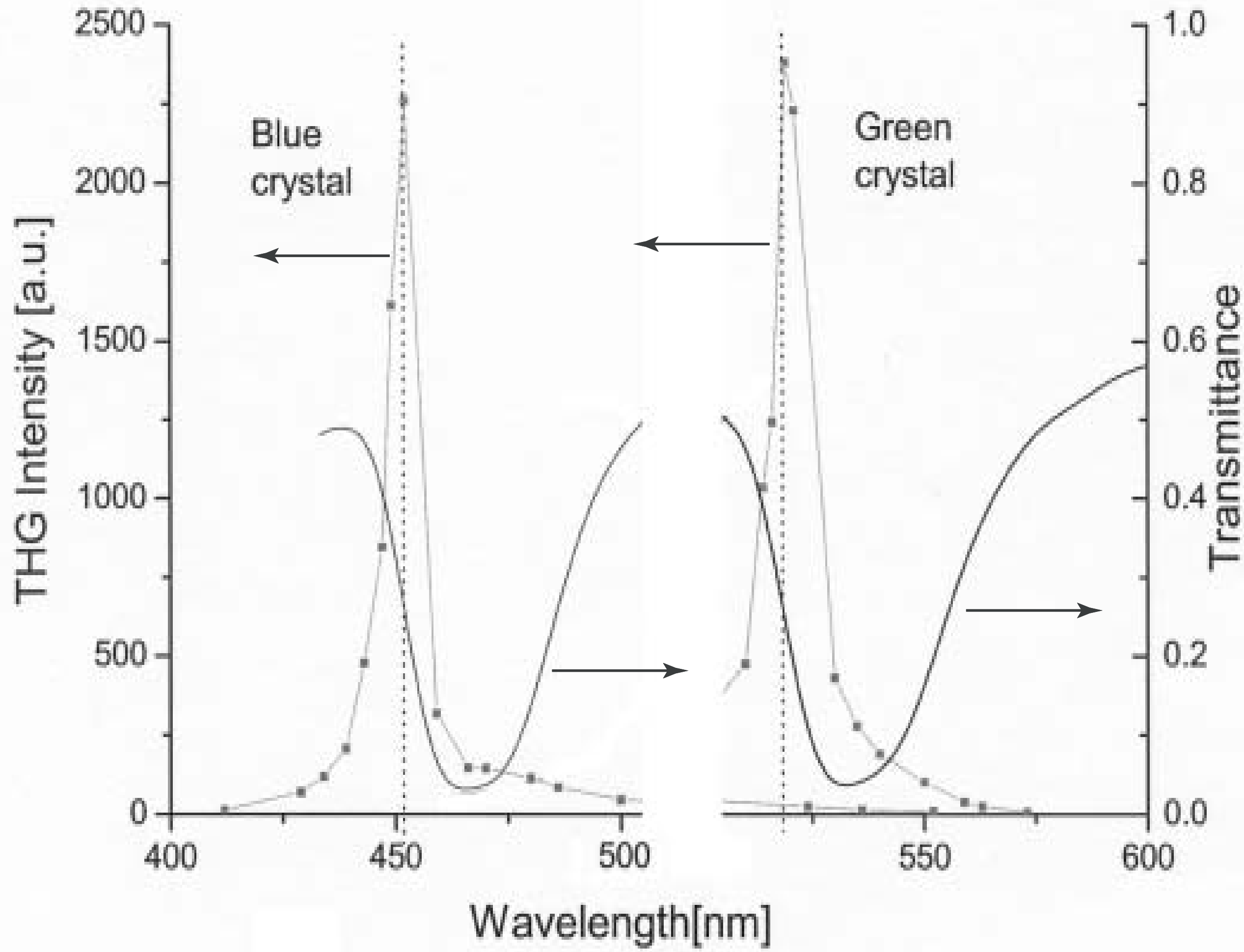
with Deborah Jackson, JPL

Third Harmonic Generation in a 3-D Photonic Crystal



polystyrene photonic crystal

Direct THG visible by eye!



Phase matching provided by PBG structure.
Joint with P.N. Prasad et al., SUNY Buffalo
Accepted for publication in PRL.

Research in Quantum Imaging

Can the images be formed with higher resolution or better sensitivity through use of quantum states of light?

Can we "beat" the Rayleigh criterion?

Quantum states of light: For instance, squeezed light or entangled beams of light.

Founders: Fabre, Klyshko, Kolobov, Kumar, Lugiato, Saleh, Sergienko, Shih, Teich.

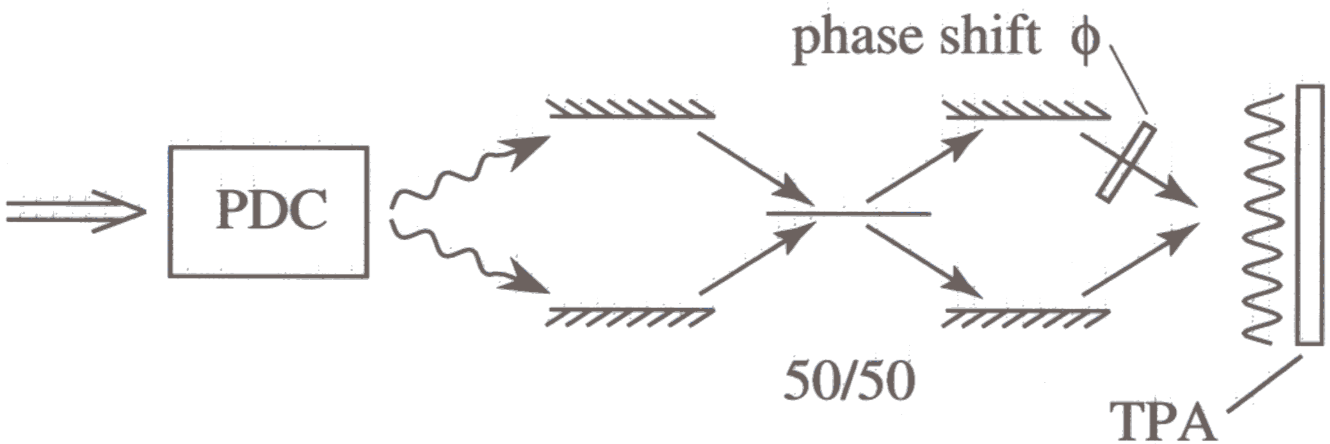
Research in Quantum Imaging

Quantum Imaging or Quantum Imogene?

Sid Caesar and
Imogene Coca in 1953

Quantum Lithography and Microscopy

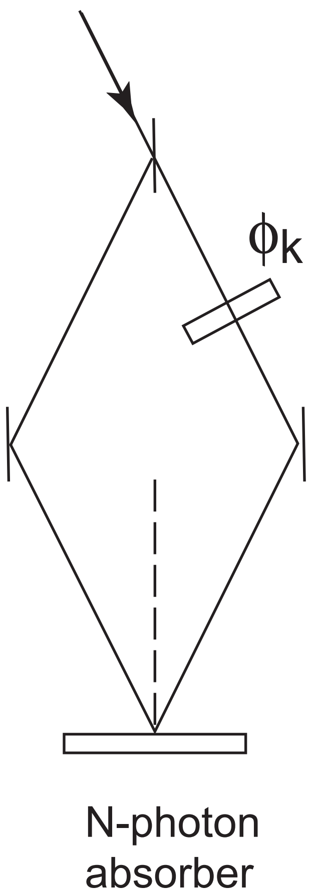
- Entangled photons can be used to form interference patterns with detail finer than the Rayleigh limit
- Process "in reverse" performs sub-Rayleigh microscopy

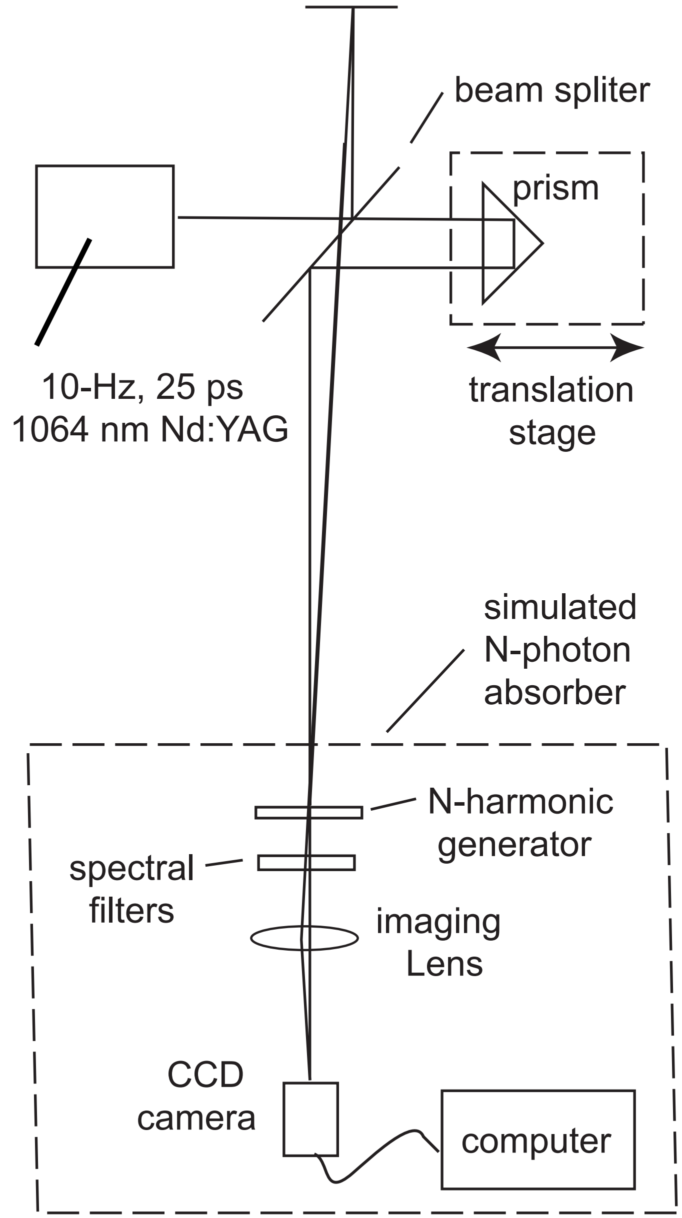


Boto et al, Phys. Rev. Lett. 85, 2733, 2000.

Non-Quantum Quantum Lithography

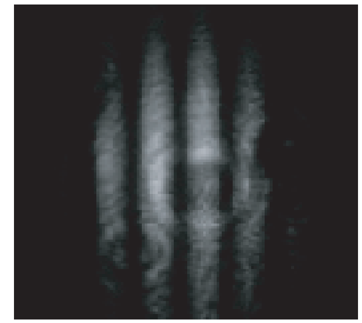
Concept: average M shots with the phase of shot k given by $2\pi k/M$



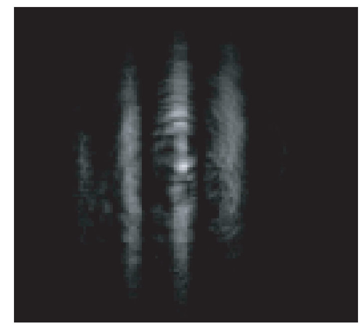


with Sean Bentley

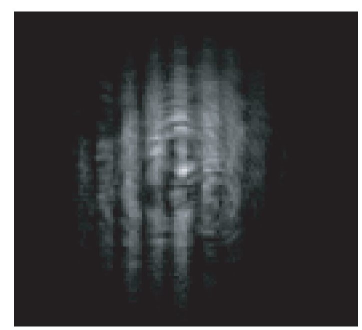
N=1, M=1



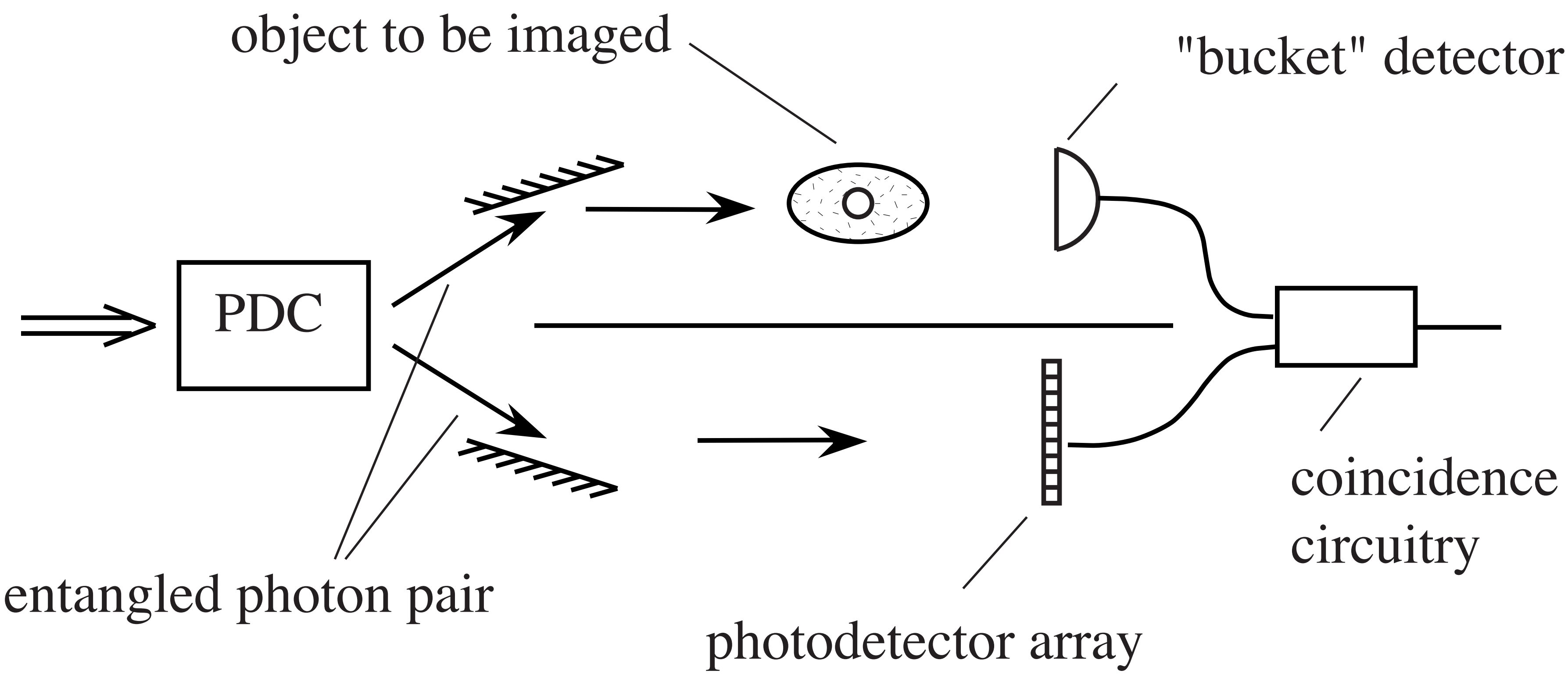
N=2, M=1



N=2, M=2



Quantum(?) Coincidence Imaging

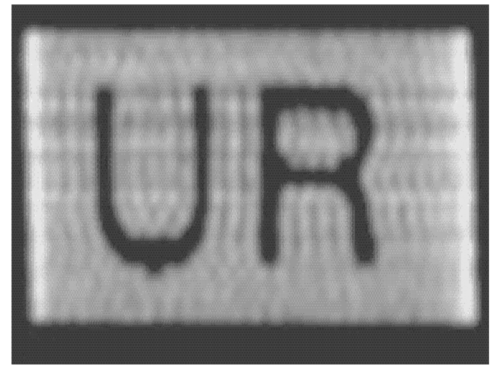


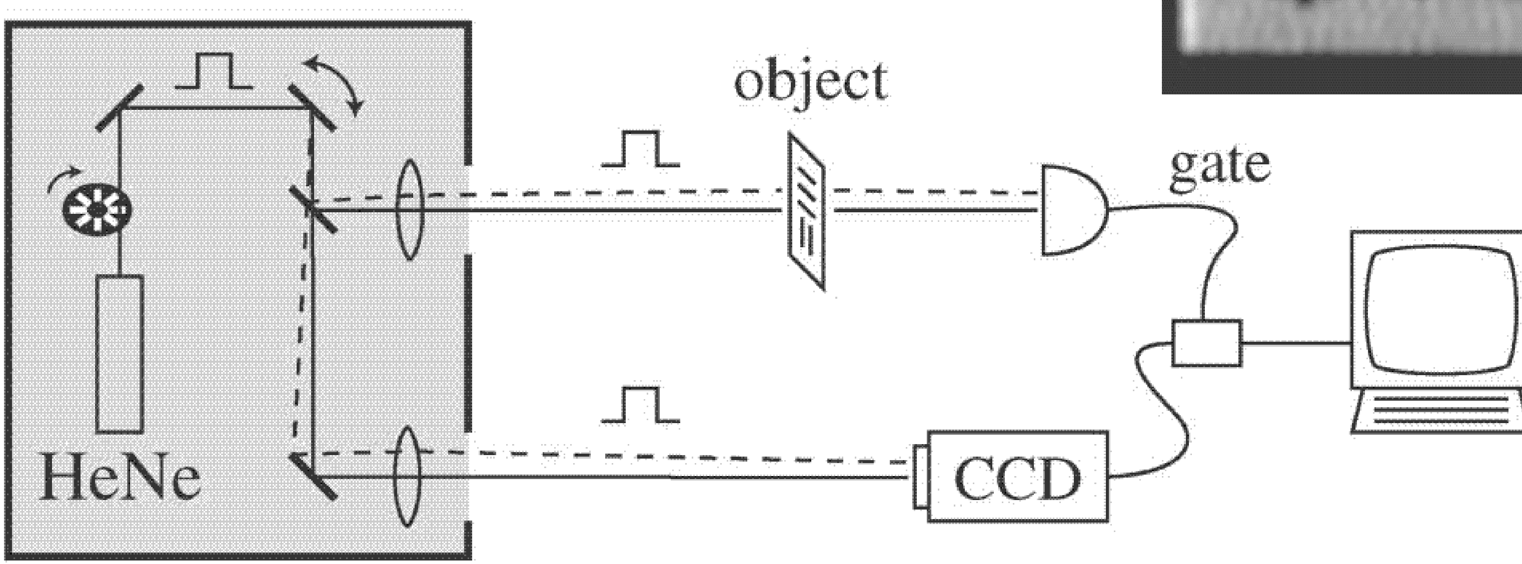
Obvious applicability to remote sensing!

Strekalov et al., Phys. Rev. Lett. **74**, 3600 (1995).
Pittman et al., Phys. Rev. A **52** R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. **87**, 123602 (2001).

Classical Coincidence Imaging

We have performed coincidence imaging with a demonstrably classical source.





Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601(2002).

Recent Development

VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 4 APRIL 2003

Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

A. Gatti, E. Brambilla, and L. A. Lugiato

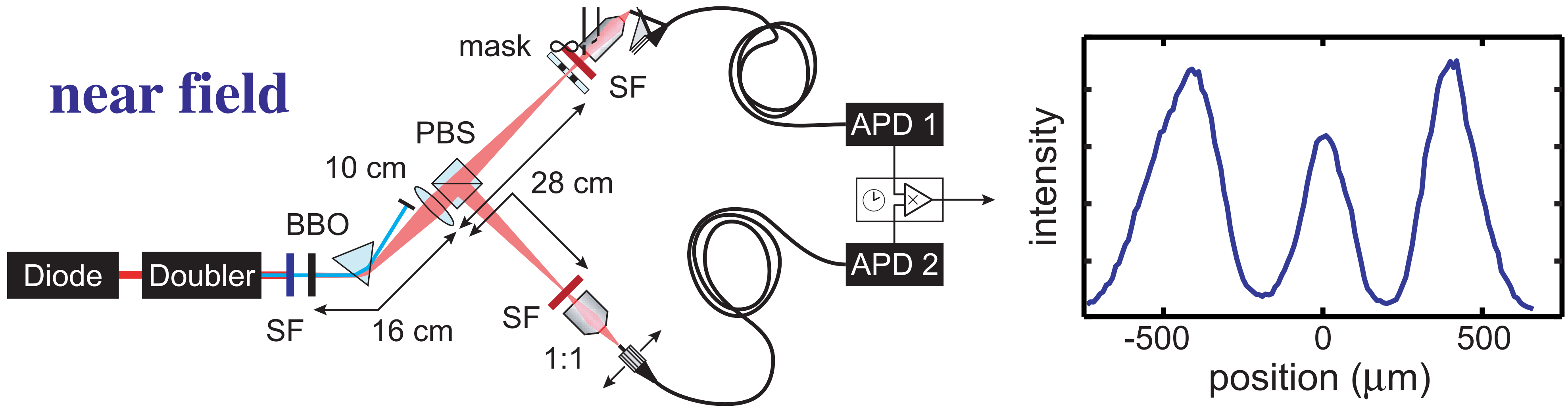
INFM, Dipartimento di Scienze CC.FF.MM., Università dellíInsubria, Via Valleggio 11, 22100 Como, Italy

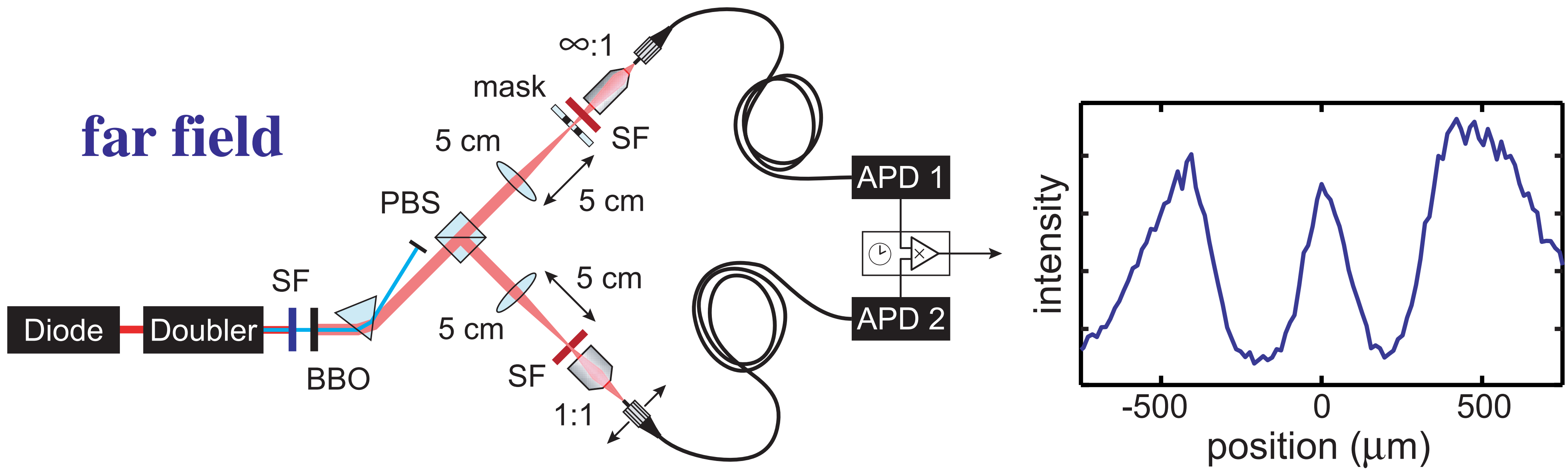
(Received 11 October 2002; published 3 April 2003)

We formulate a theory for entangled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

DOI: 10.1103/PhysRevLett.90.133603 PACS numbers: 42.50.Dv, 03.65.Ud

Near- and Far-Field Imaging Using Quantum Entanglement





Good imaging observed in both the near and far fields.

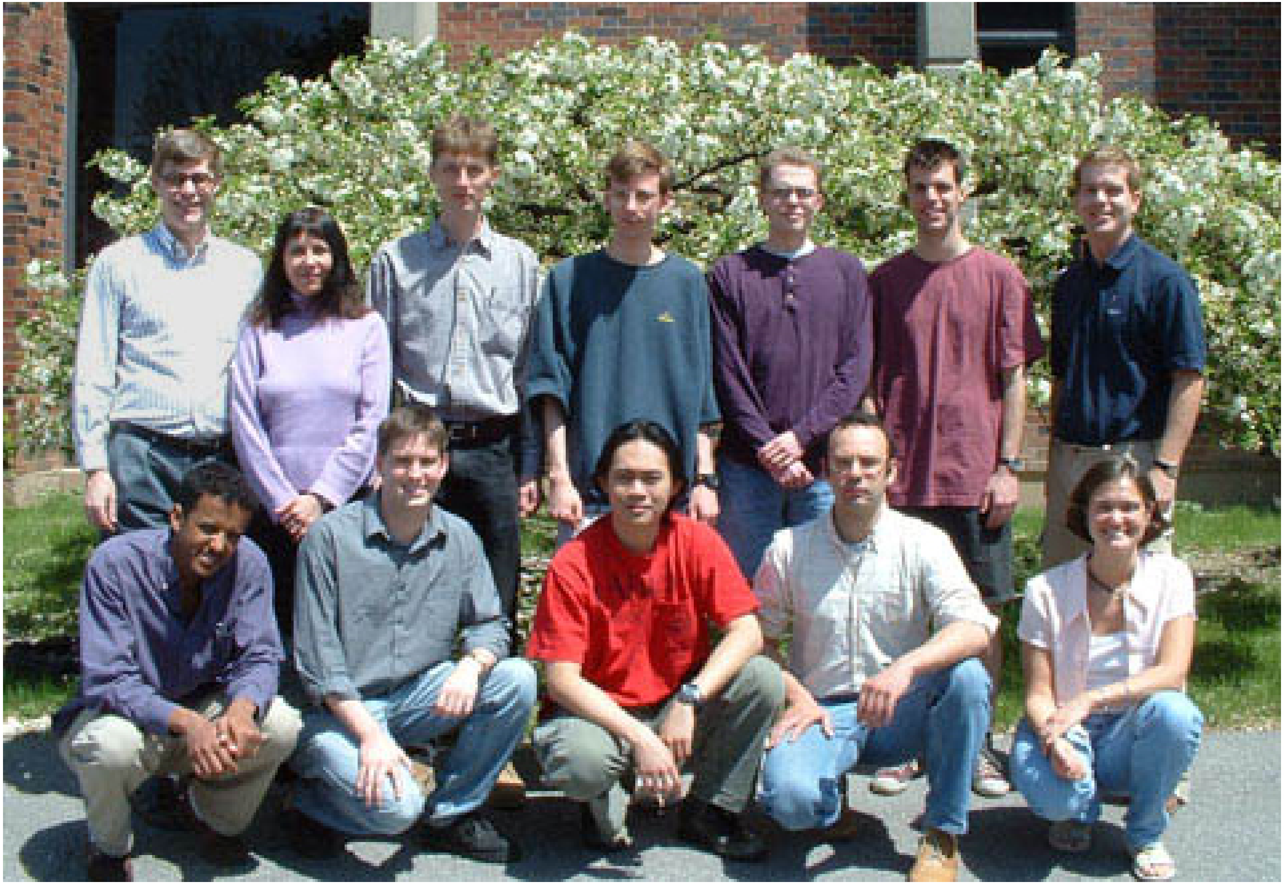
R. Bennink, S. Bentley, R. Boyd, and J. Howell; Howell, Wed 9:50; Bennink, Thur 12:40

Summary

Demonstration of room temperature superluminal propagation in alexandrite and slow light in ruby

Observation of the quantum signature of coincidence imaging and demonstration of position-momentum EPR paradox

Special Thanks to my Students and Research Associates



Thank you for your attention.