Slow Light, Fast Light, and their Applications

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with Yuping Chen, George Gehring, Giovanni Piredda,
Aaron Schweinsberg, Katie Schwertz, Zhimin Shi, Heedeuk Shin,
Petros Zerom, and many others

Presented at the OSA Conference on Slow and Fast Light, July 23-26, 2006,
Washington, DC.

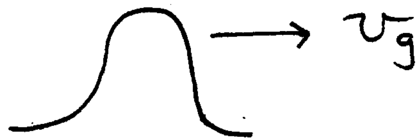
Outline of the Presentation

1. How to slow down the speed of light - conceptual matters
2. Slow light using electromagnetically induced transparency
3. Slow light in room temperature solids
4. What about fast light (group velocity > c)?
5. Applications of slow and fast light

Overview: Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.

Group Velocity

Pulse
(wave packet)



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

For $\quad k = \dfrac{n\omega}{c} \qquad \dfrac{dk}{d\omega} = \dfrac{1}{c}\left(n + \omega \dfrac{dn}{d\omega}\right)$

Thus

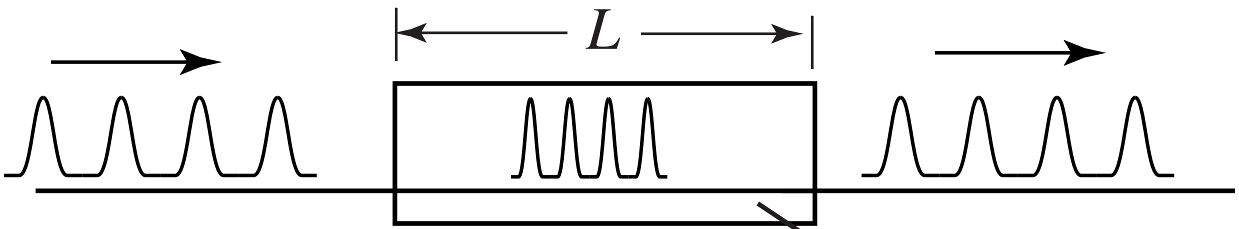
$$v_g = \frac{c}{n + \omega \frac{dn}{d\omega}} \equiv \frac{c}{n_g}$$

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

Dispersion of Water Waves

* from F. Bitter and H. Medicus, Fields and particles; an introduction to electromagnetic wave phenomena and quantum physics

Review of Slow-Light Fundamentals



group velocity: $v_g = \dfrac{c}{n_g}$

group index: $n_g = n + \omega \dfrac{dn}{d\omega}$

group delay: $T_g = \dfrac{L}{v_g} = \dfrac{L n_g}{c}$

controllable delay: $T_{\text{del}} = T_g - L/c = \dfrac{L}{c}(n_g - 1)$

To make controllable delay as large as possible:

- make L as large as possible (reduce residual absorption)
- maximize the group index

Switch to Overheads

Approaches to Slow Light Propagation

- Use of quantum coherence (to modify the spectral dependence of the atomic response)

  e.g., electromagnetically induced transparency

- Use of artificial materials (to modify the optical properties at the macroscopic level)

  e.g., photonic crystals (strong spectral variation of refractive index occurs near edge of photonic bandgap)

- Want v_g very different from v_p

Need very large dispersion

Study resonances of atomic vapor

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

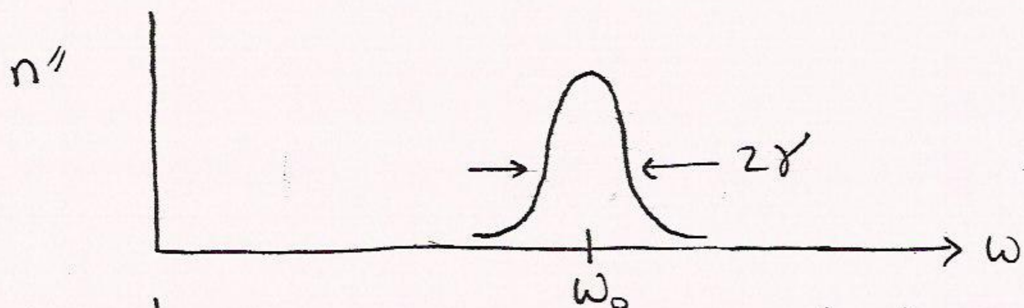
Light Propagation in Atomic Vapors

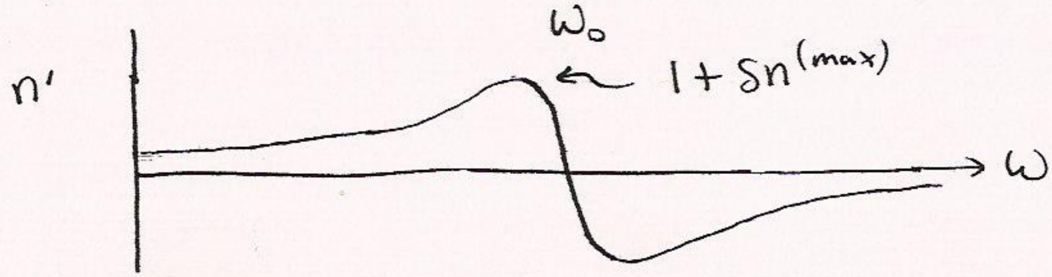
$$n = \sqrt{\varepsilon} = \sqrt{1 + 4\pi\chi} \qquad \chi = \frac{Ne^2/2m\omega_0}{(\omega_0 - \omega) - i\gamma}$$

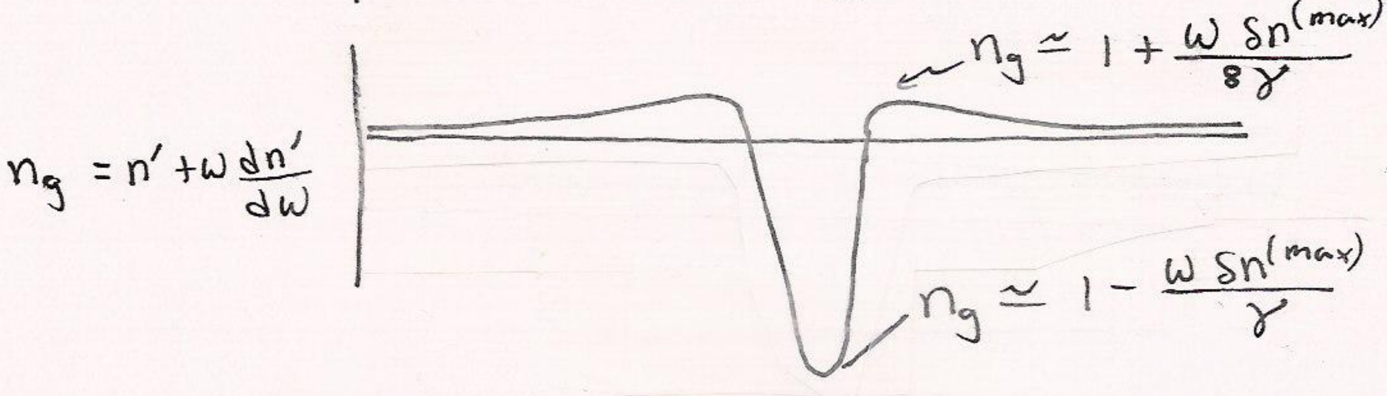
For N not too large, $n = n' + i n'' \simeq 1 + 2\pi\chi$

$$n' \simeq 1 + \frac{\pi N e^2}{m\omega_0} \, \frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 + \gamma^2}$$

$$n'' = \frac{\pi N e^2}{2m\omega_0\gamma} \, \frac{\gamma^2}{(\omega_0 - \omega)^2 + \gamma^2}$$







$$\frac{\omega\,\delta n^{(max)}}{\gamma} \approx \frac{2\pi(5\times10^{14})(0.1)}{2\pi(1\times10^{9})} = 5\times10^{4} \sim (!)$$

n_g can range from $+5\times10^4$ to -5×10^4.

(But with lots of absorption)

Slow Light in Atomic Vapors

Need to minimize absorption

- Work far off resonance
  (See papers of Howell group at this conference)

- Work on resonance and use electromagnetically induced transparency (EIT)
  (Hau, Harris, Welch, Scully, Budker, and many others)

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

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

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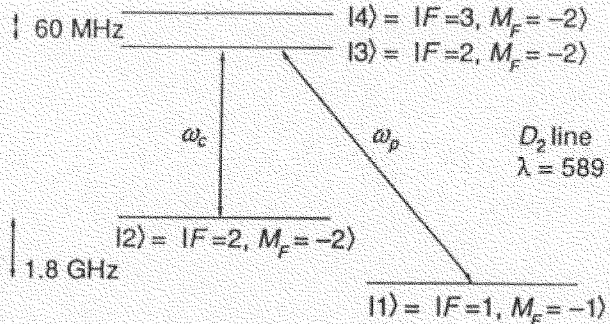
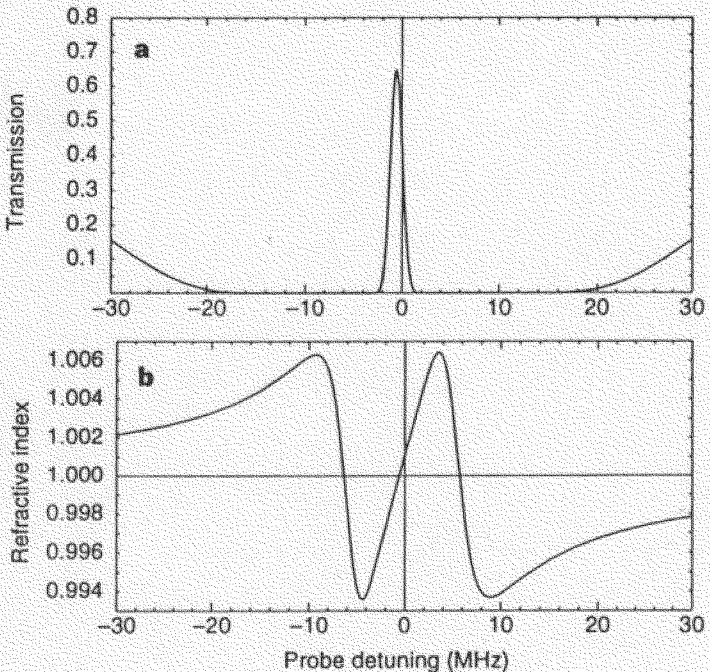
† *Department of Physics,* § *Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*

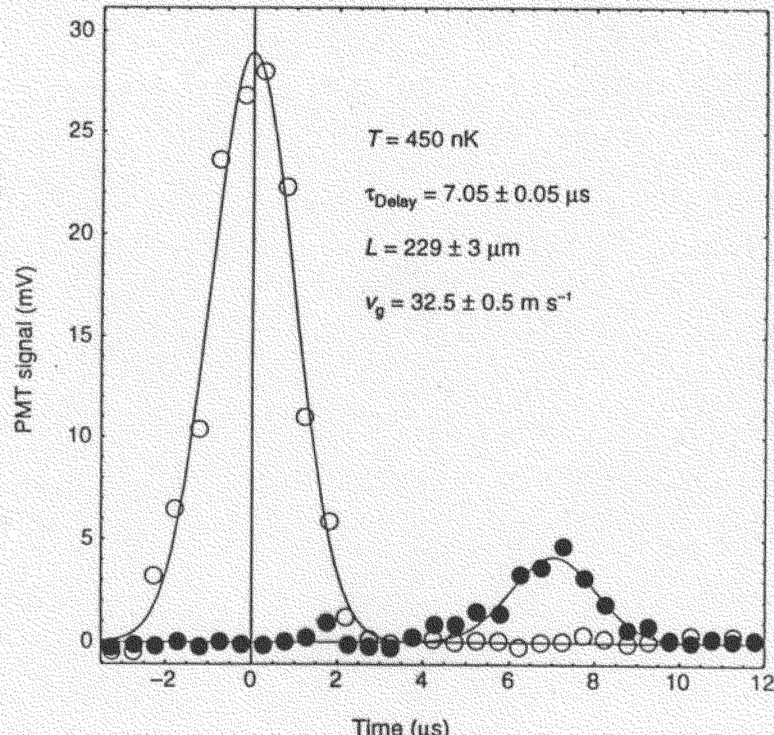
‡ *Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

Nature, 397, 594, (1999).



$$v_g = \frac{c}{n(\omega_p) + \omega_p \frac{dn}{d\omega_p}} \approx \frac{\hbar c \epsilon_0}{2\omega_p} \frac{|\Omega_c|^2}{|\mu_{13}|^2 N}$$





Challenge/Goal

Slow light in a room-temperature solid-state material.

Solution: Slow light enabled by coherent population oscillations (a quantum coherence effect that is relatively insensitive to dephasing processes).

Slow Light in Ruby

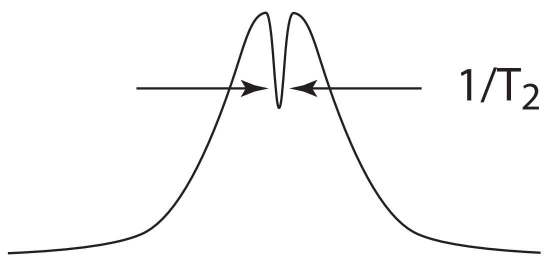
Recall that $n_g = n + \omega(dn/d\omega)$. Need a large $dn/d\omega$. (How?)

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

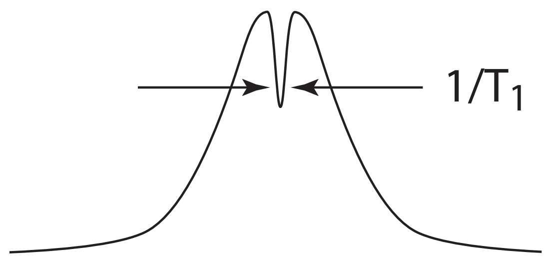
Well-known "trick" for doing so:

Make use of spectral holes due to population oscillations.

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



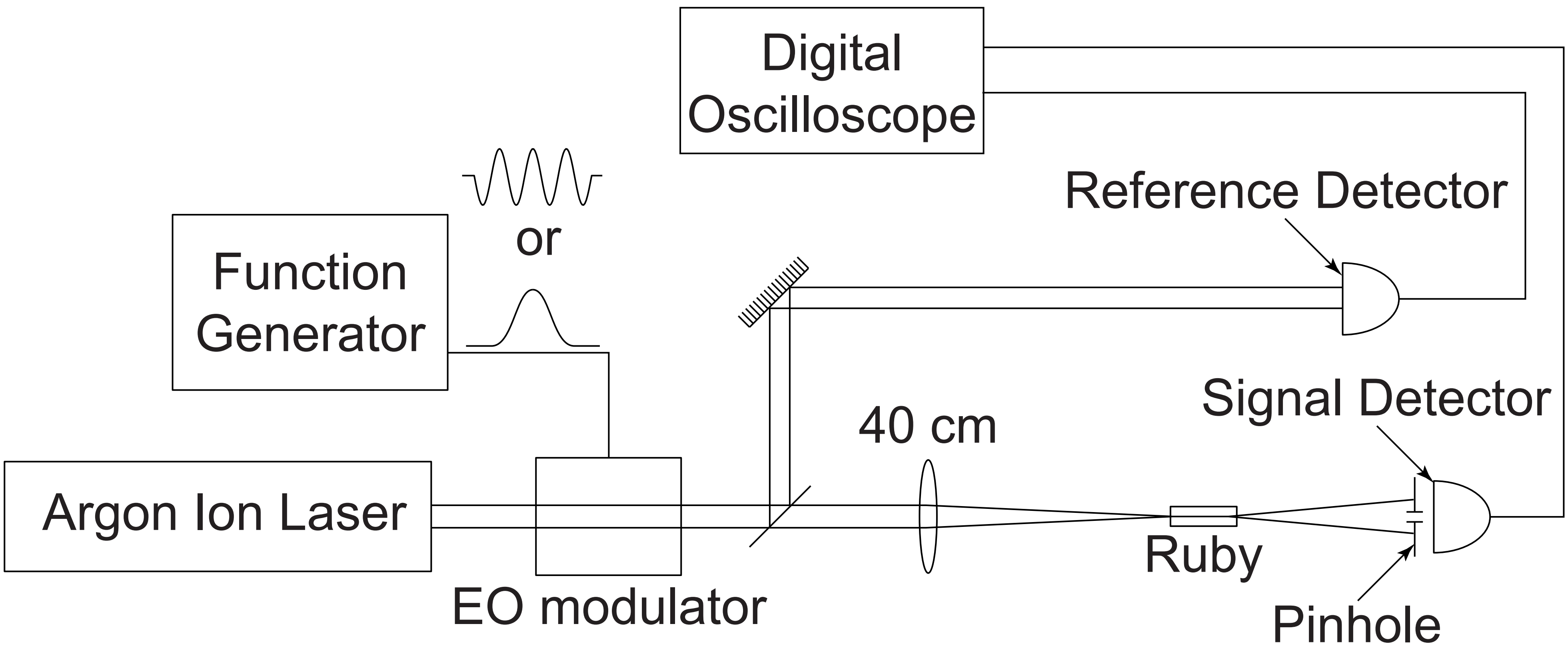
inhomogeneously broadened medium



homogeneously broadened medium (or inhomogeneously broadened)

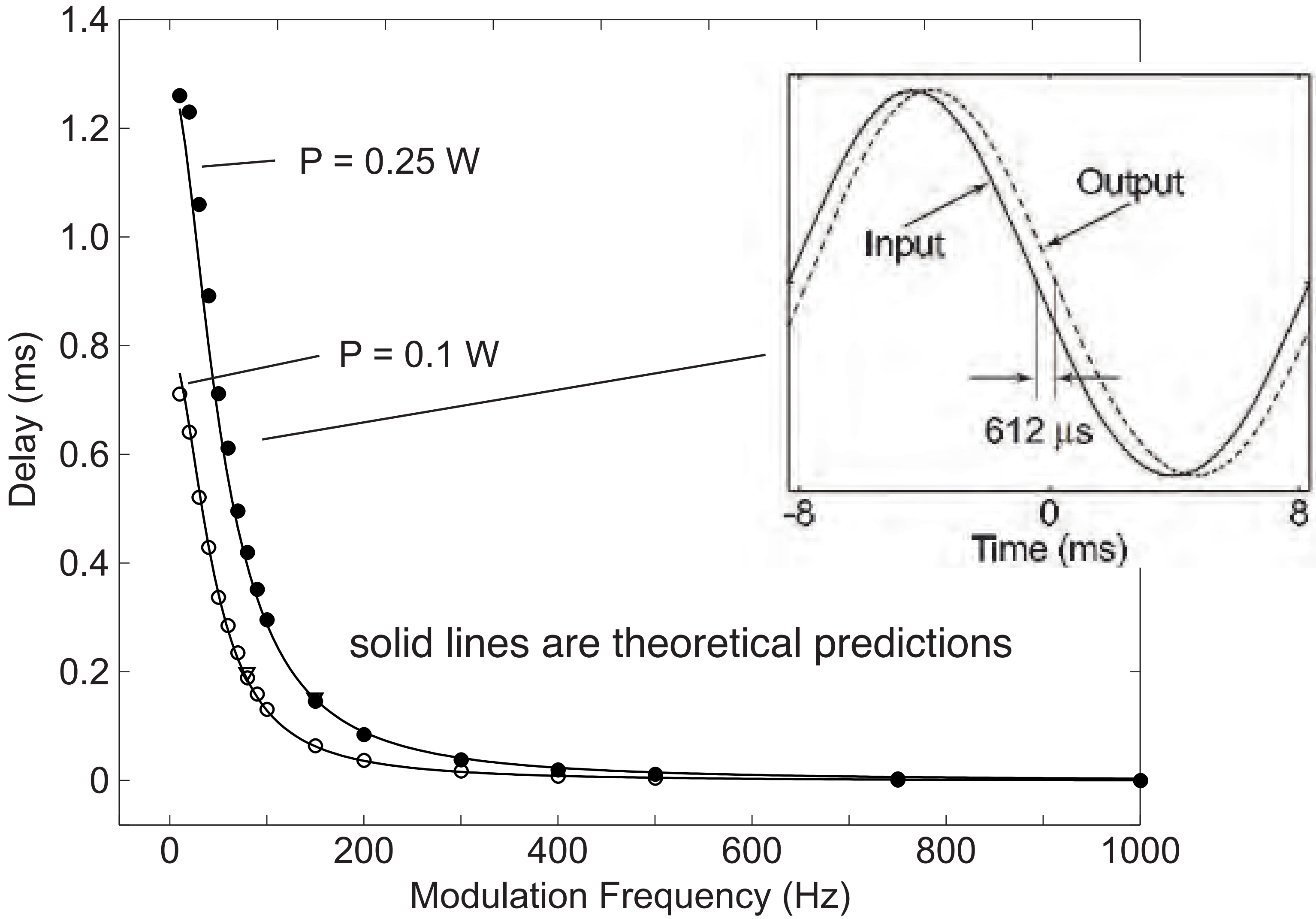
PRL 90,113903(2003).

Slow Light Experimental Setup



7.25-cm-long ruby laser rod (pink ruby)

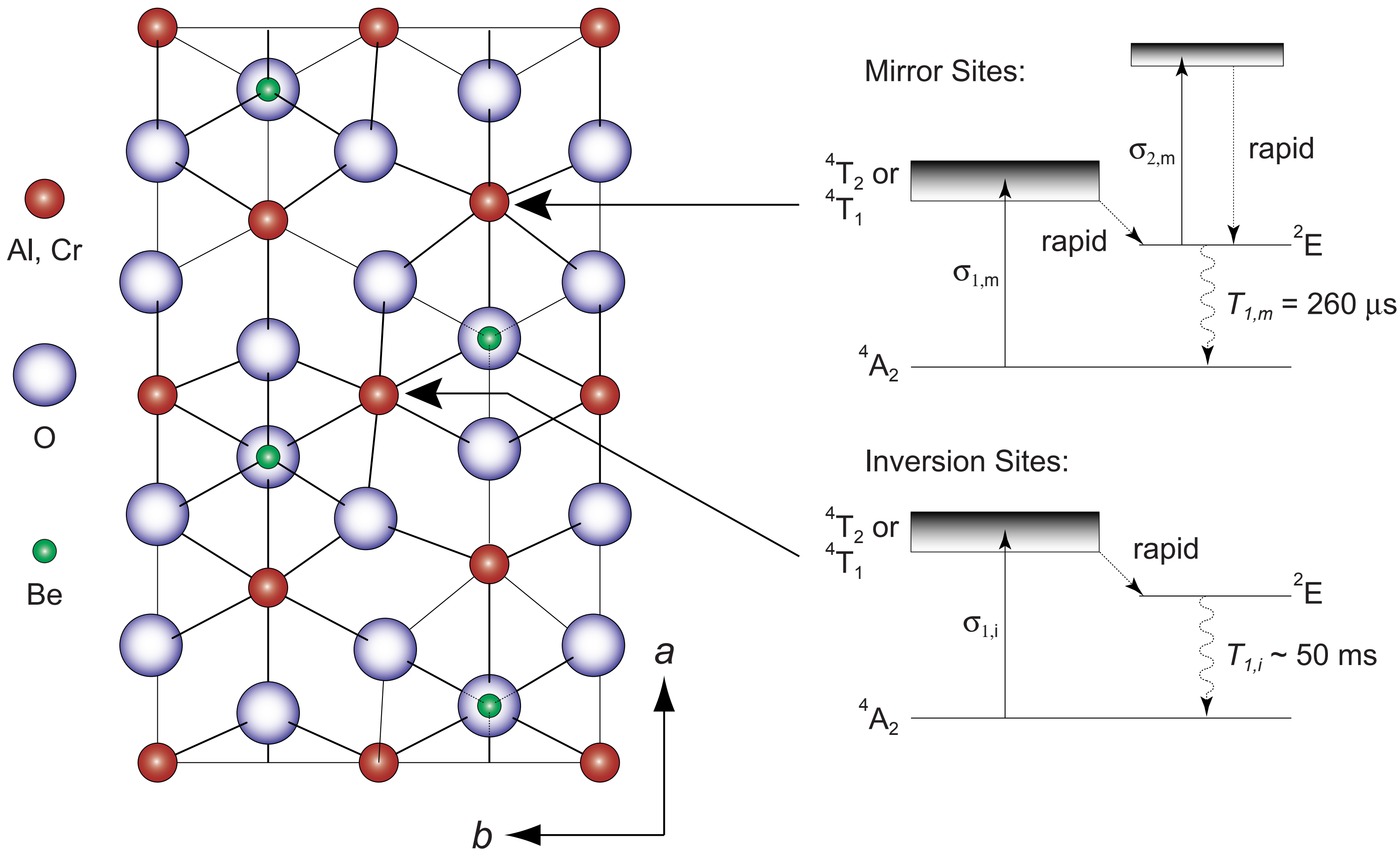
Measurement of Delay Time for Harmonic Modulation



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

Alexandrite Displays both Saturable and Reverse-Saturable Absorption

- Both slow and fast propagation observed in alexandrite

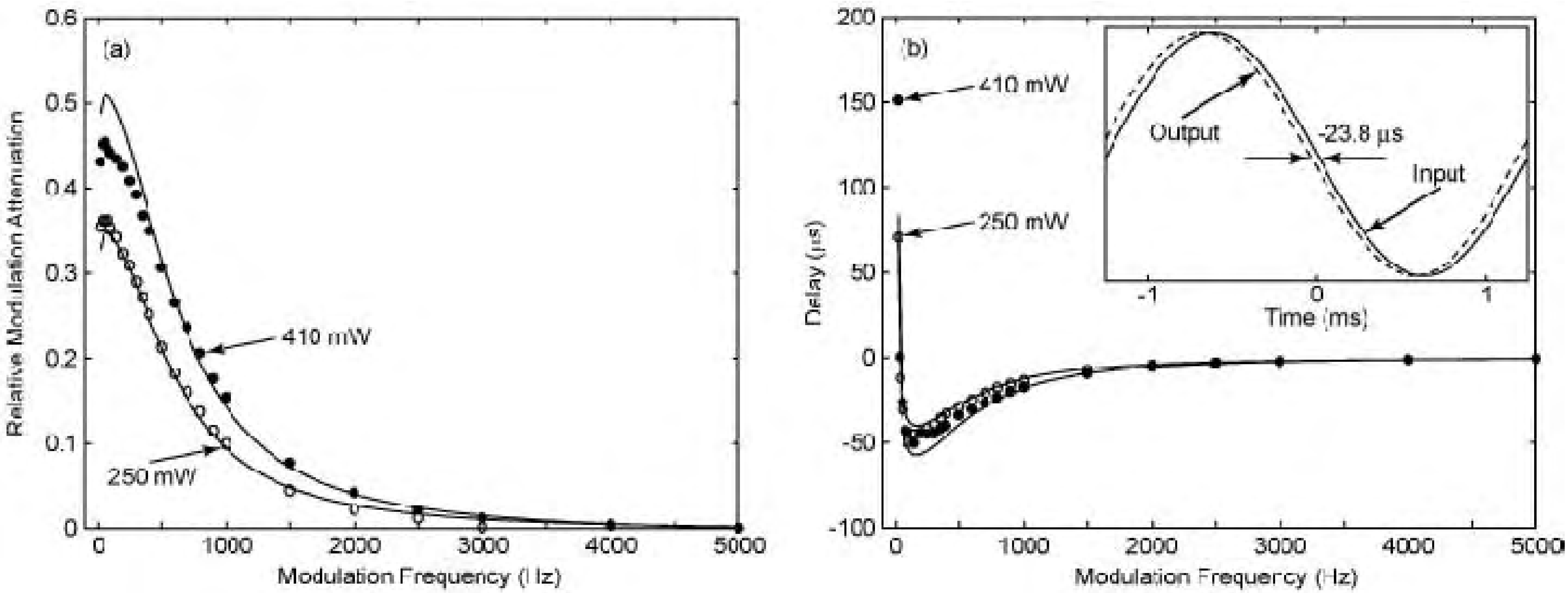


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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

Numerical Modeling of Pulse Propagation Through Slow and Fast-Light Media

Numerically integrate the paraxial wave equation

$$\frac{\partial A}{\partial z} - \frac{1}{v_g}\frac{\partial A}{\partial t} = 0$$

and plot $A(z,t)$ versus distance z.

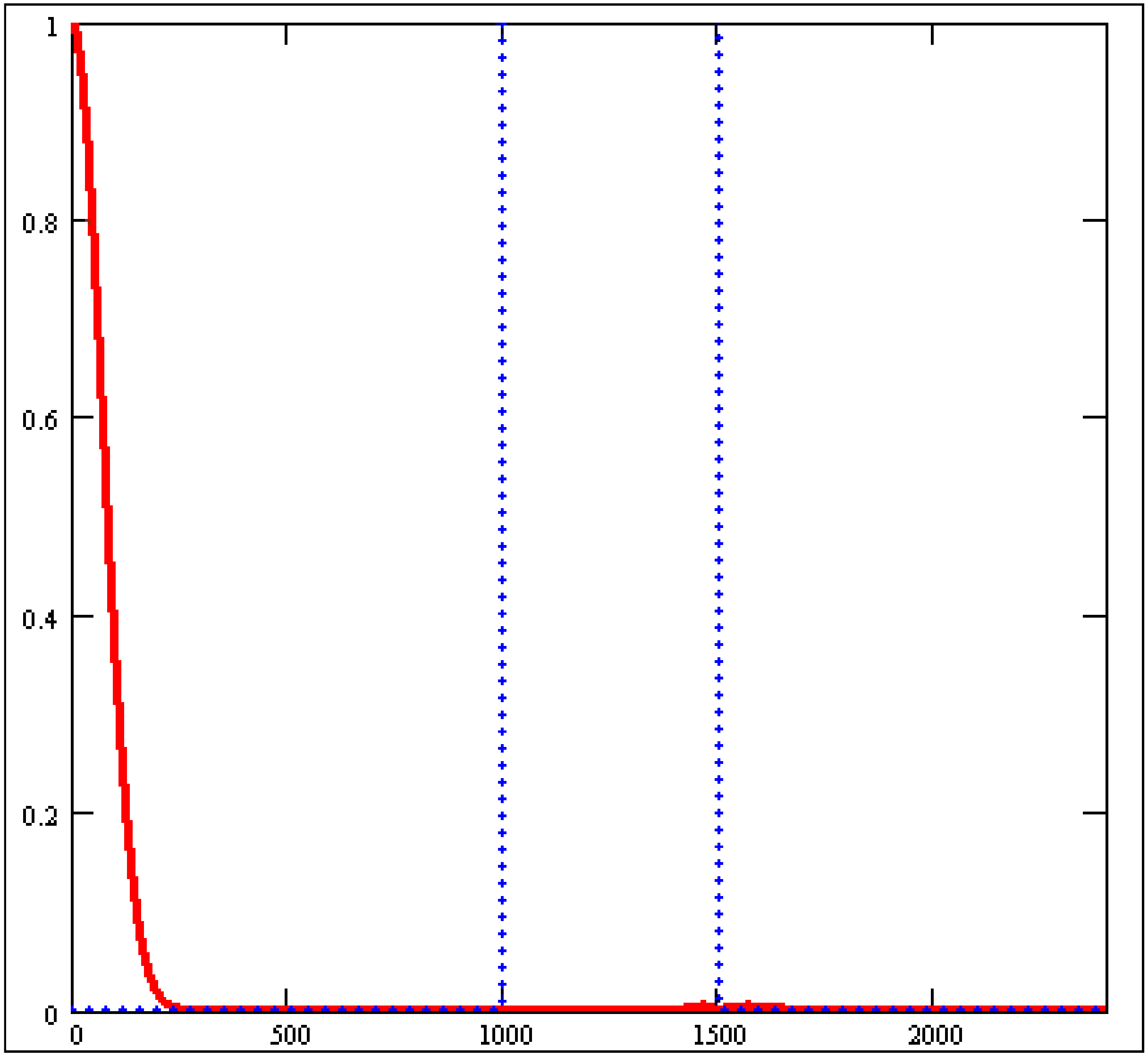
Assume an input pulse with a Gaussian temporal profile.

Study three cases:

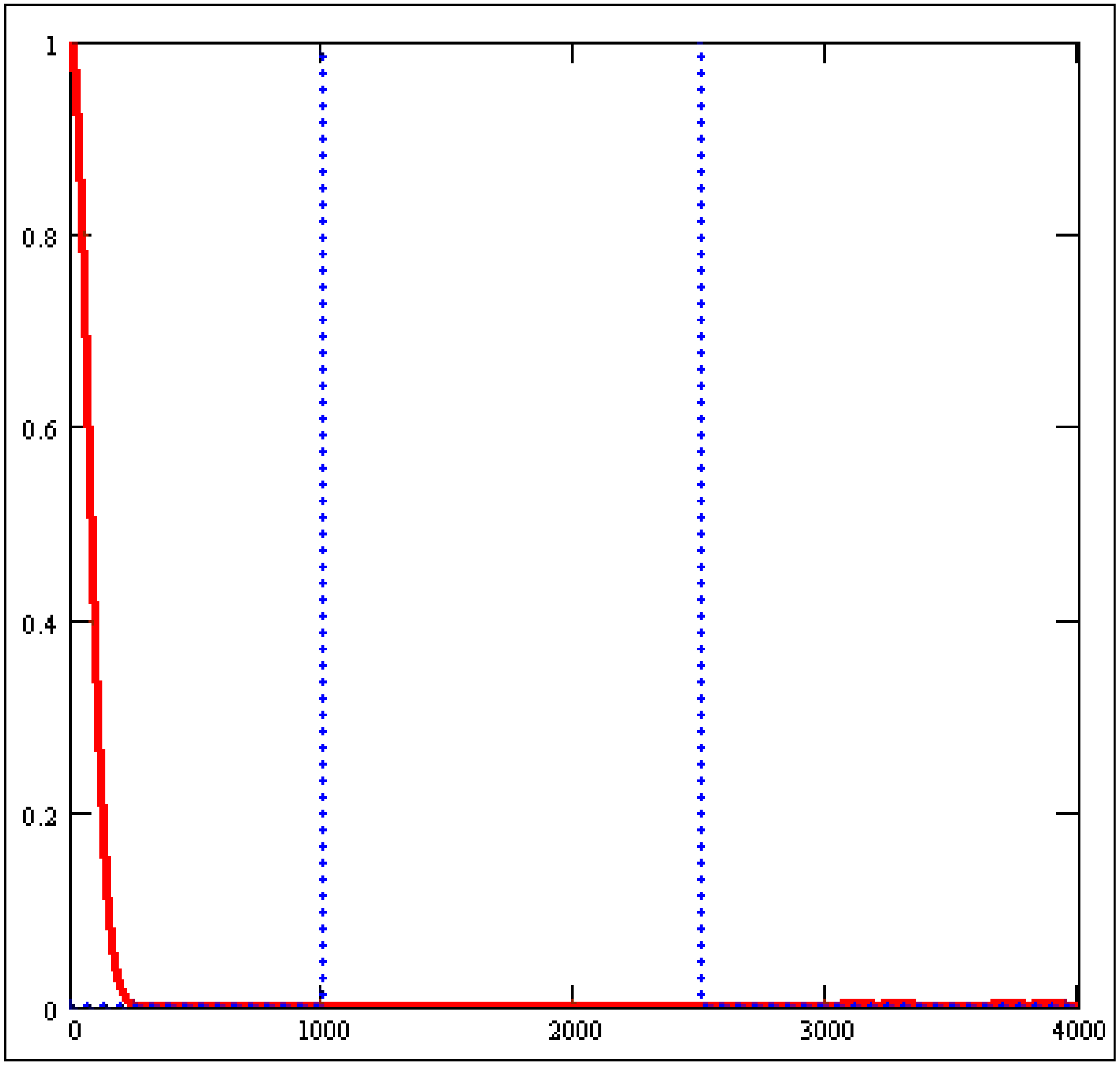
Slow light $v_g = 0.5\ c$

Fast light $v_g = 5\ c$ and $v_g = -2\ c$

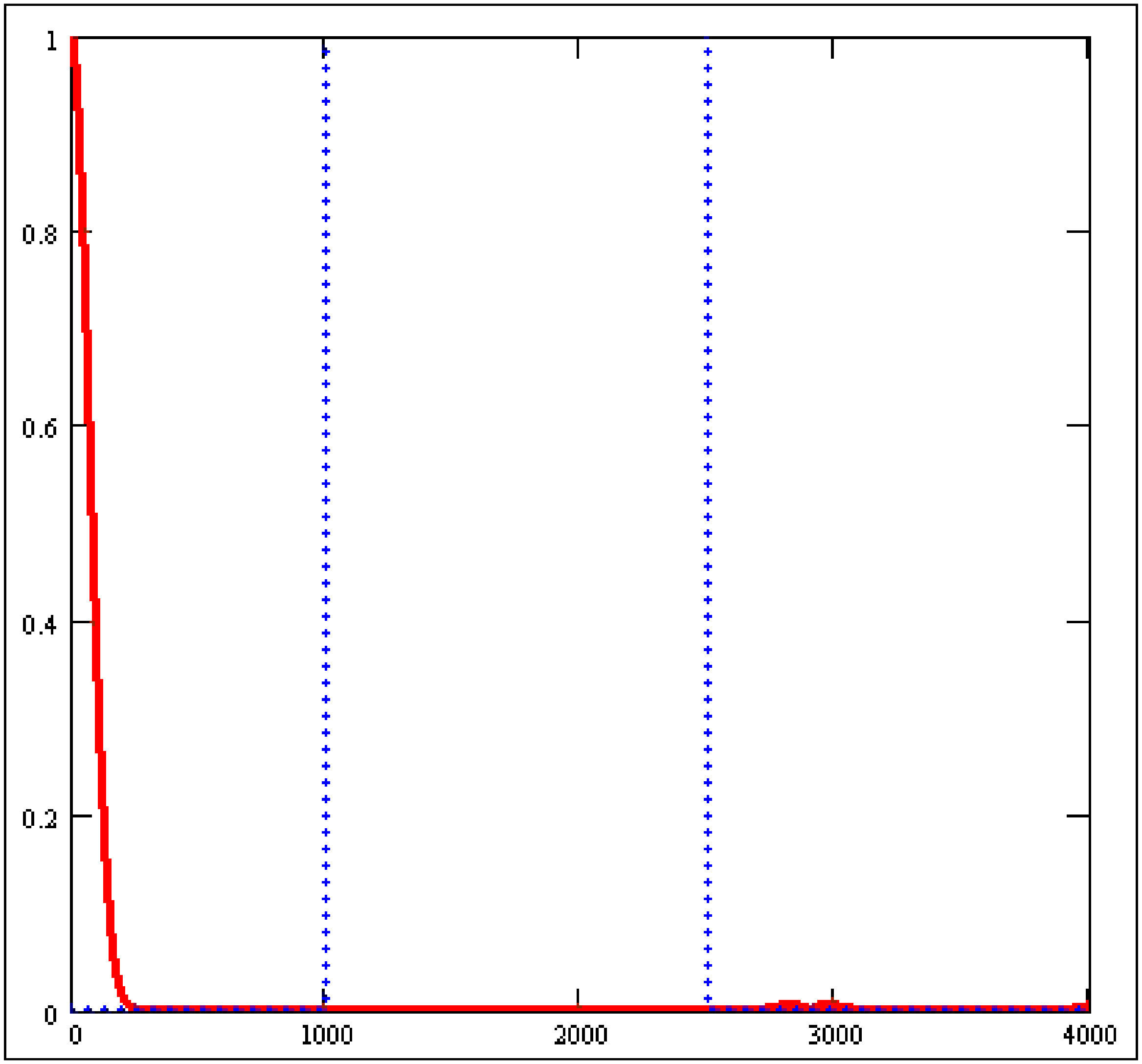
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



Pulse Propagation through a Fast-Light Medium ($n_g = .2$, $v_g = 5$ c)

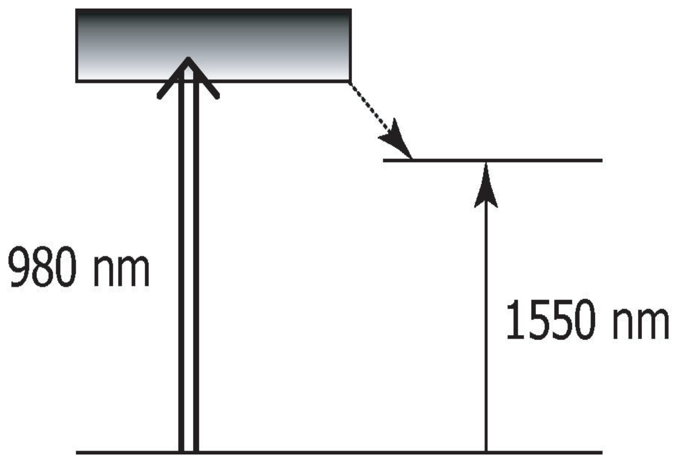


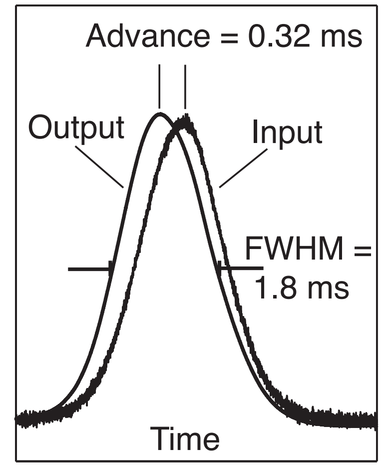
Pulse Propagation through a Fast-Light Medium (n_g = -.5, v_g = -2 c)

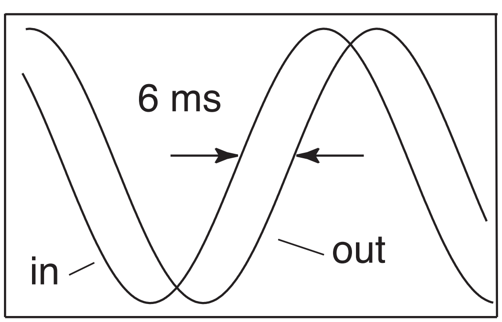


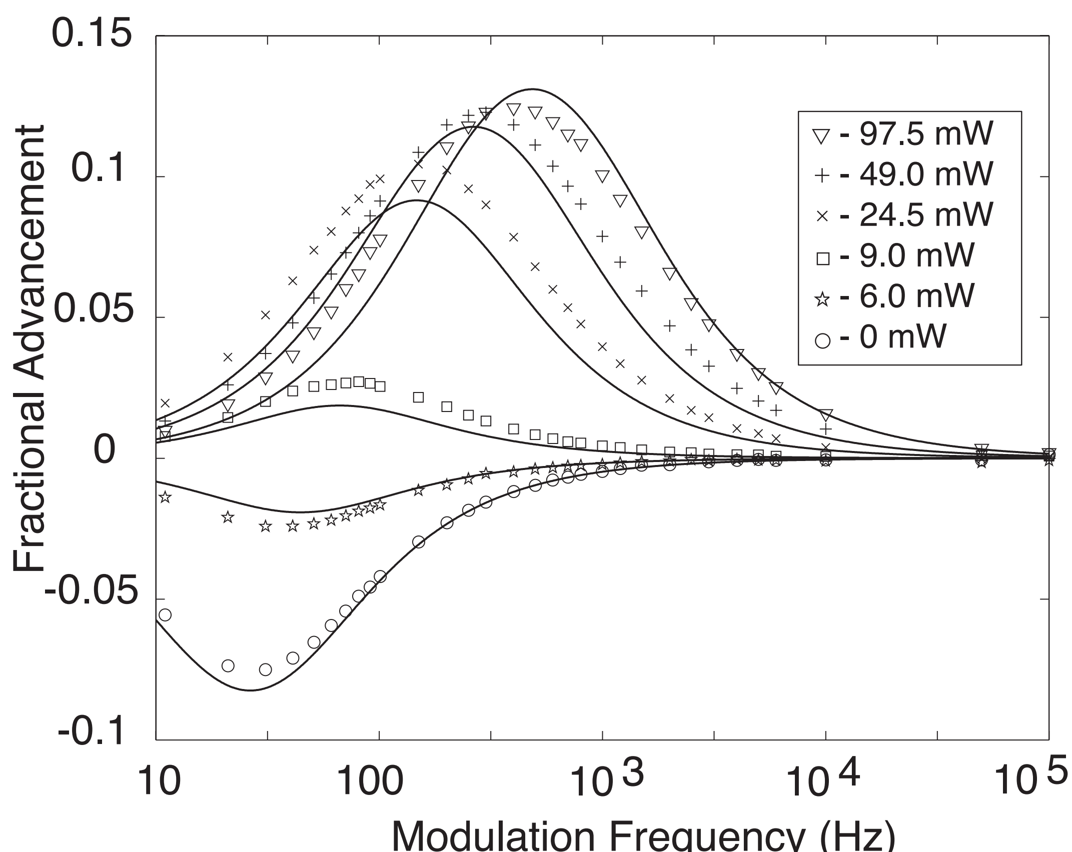
Slow and Fast Light in an Erbium Doped Fiber Amplifier

- Fiber geometry allows long propagation length
- Saturable gain or loss possible depending on pump intensity



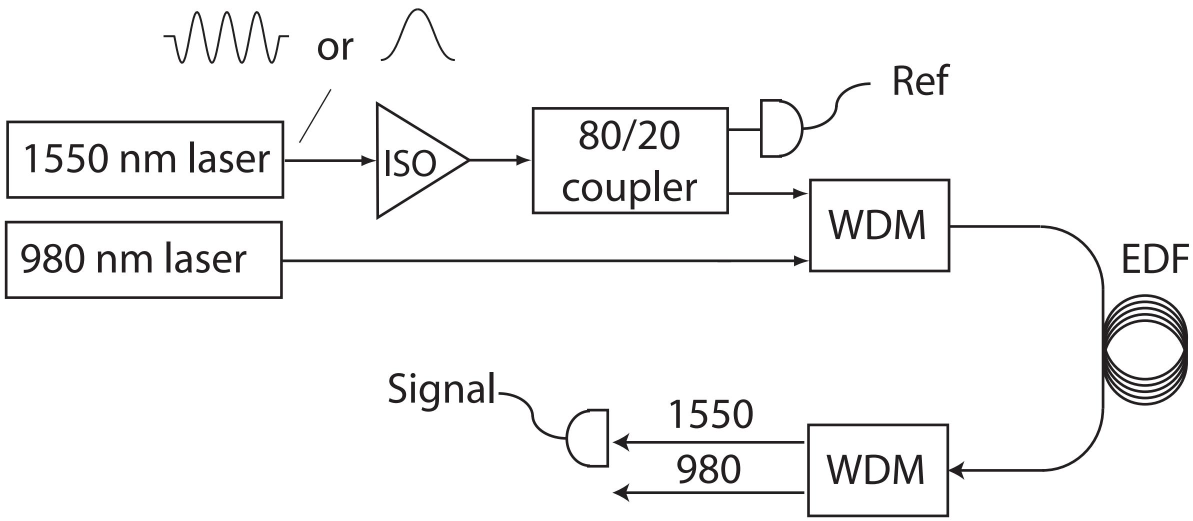






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

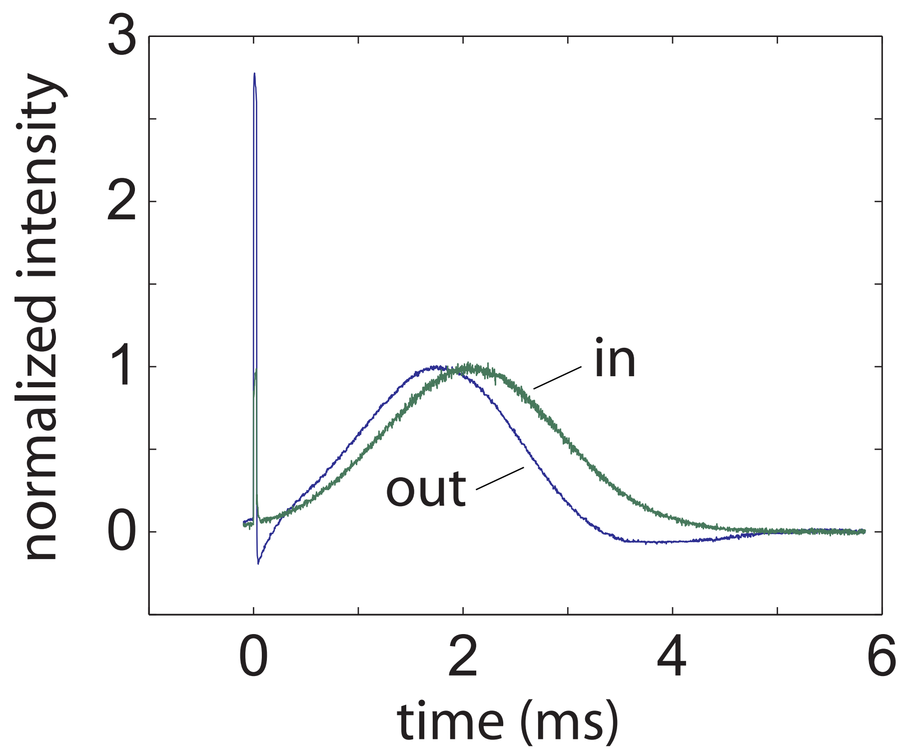
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



We time-resolve the propagation of the pulse as a function of position along the erbium-doped fiber.

Procedure

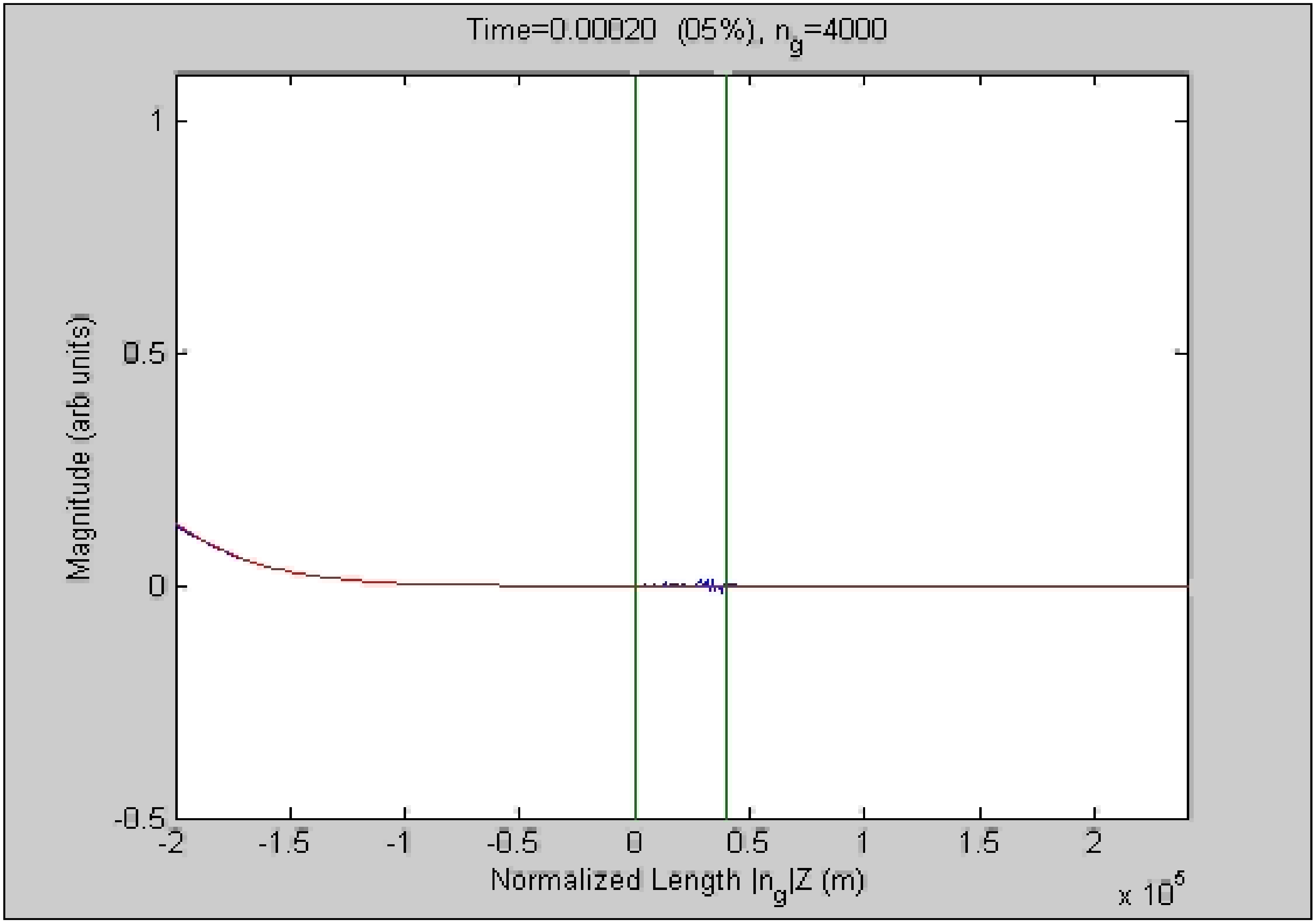
- cutback method
- couplers embedded in fiber



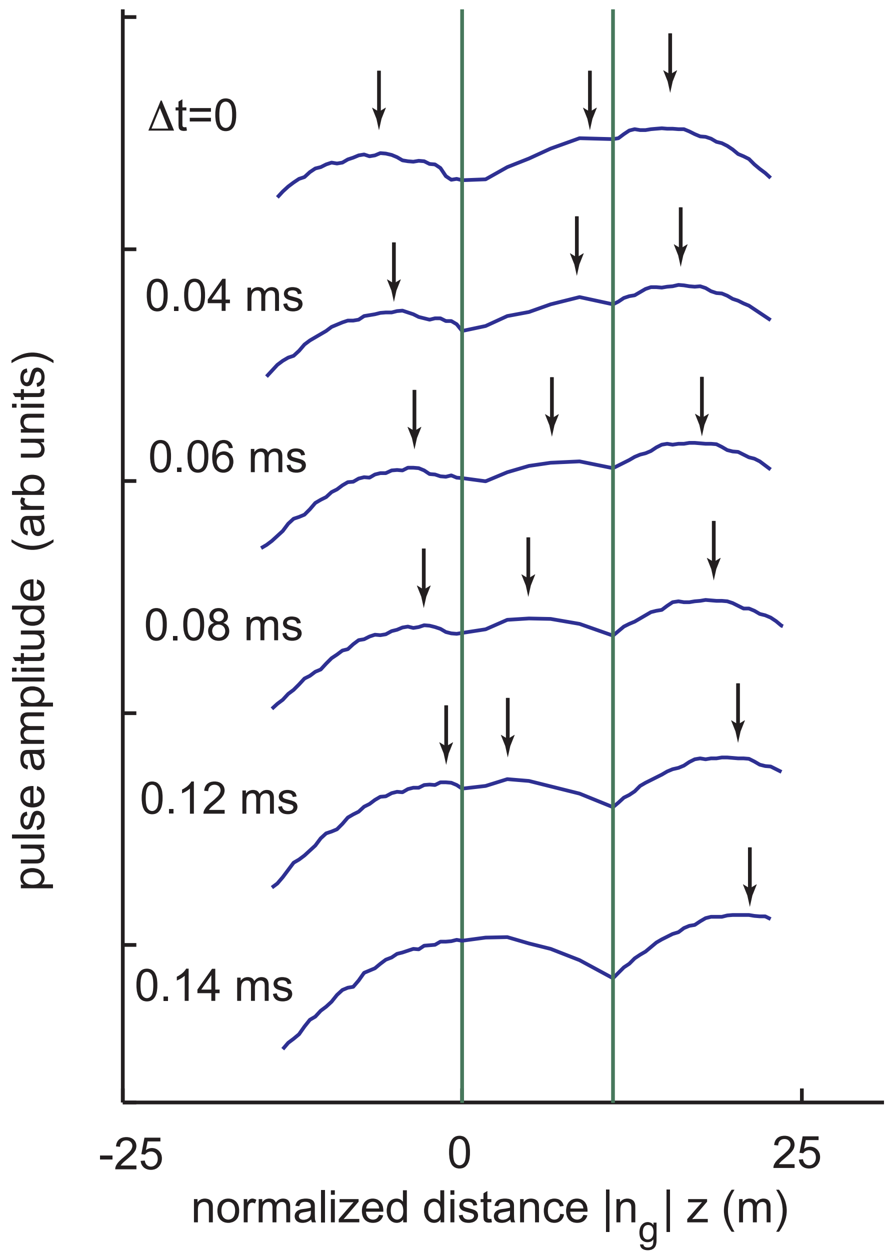
G. M. Gehring, A. Schweinsberg, C. Barsi, N. Kostinski, R. W. Boyd, Science 312, 985 2006.

Experimental Results: Backward Propagation in Erbium-Doped Fiber

Normalized: (Amplification removed numerically)



Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier

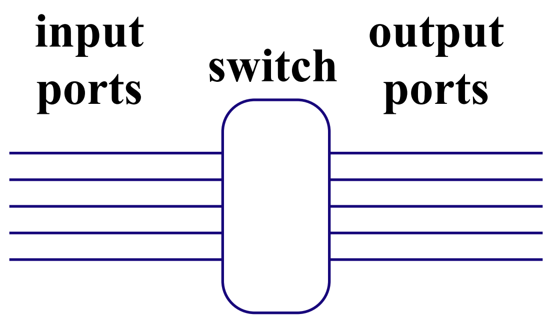
Summary:

“Backwards” propagation is a realizable physical effect.

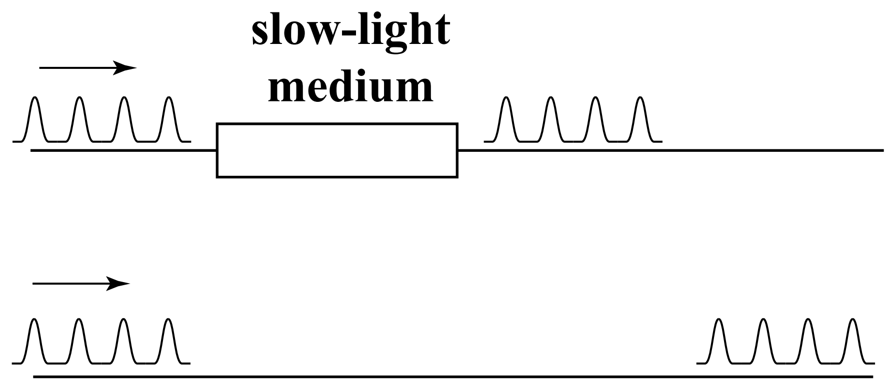
(Of course, many other workers have measured negative time delays. Our contribution was to measure the pulse evolution within the material medium.)

Slow Light and Optical Buffers

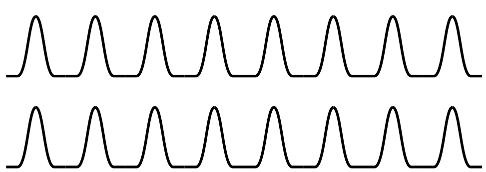
All-Optical Switch



Use Optical Buffering to Resolve Data-Packet Contention



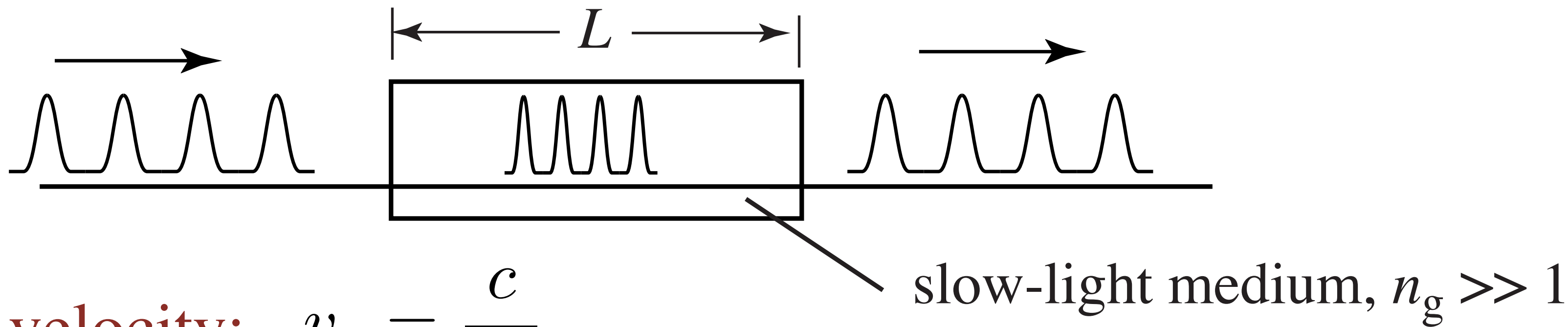
But what happens if two data packets arrive simultaneously?



Controllable slow light for optical buffering can dramatically increase system performance.

Daniel Blumenthal, UC Santa Barbara; Alexander Gaeta, Cornell University; Daniel Gauthier, Duke University; Alan Willner, University of Southern California; Robert Boyd, John Howell, University of Rochester

Review of Slow-Light Fundamentals



group velocity: $v_g = \dfrac{c}{n_g}$

group index: $n_g = n + \omega \dfrac{dn}{d\omega}$

group delay: $T_g = \dfrac{L}{v_g} = \dfrac{L n_g}{c}$

controllable delay: $T_{\mathrm{del}} = T_g - L/c = \dfrac{L}{c}(n_g - 1)$

To make controllable delay as large as possible:

- make L as large as possible (reduce residual absorption)
- maximize the group index

Systems Considerations: Maximum Slow-Light Time Delay

"Slow light": group velocities $< 10^{-6}$ c !

Proposed applications: controllable optical delay lines optical buffers, true time delay for synthetic aperture radar.

Key figure of merit:
normalized time delay = total time delay / input pulse duration
$\approx$ information storage capacity of medium

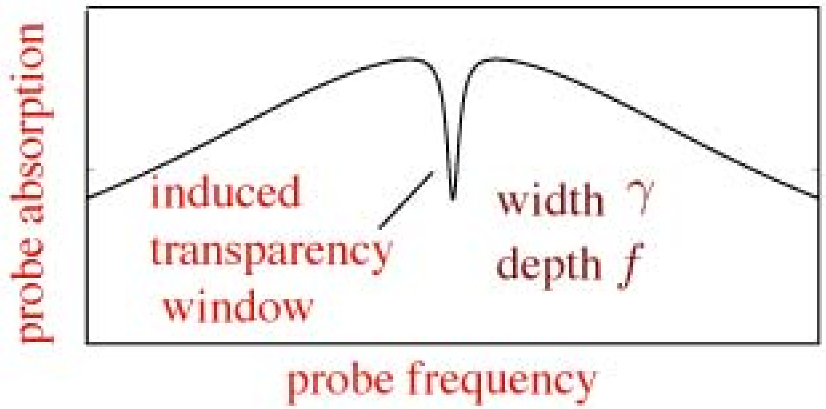
Best result to date: delay by 4 pulse lengths (Kasapi et al. 1995)

But data packets used in telecommunications contain $\approx 10^3$ bits

What are the prospects for obtaining slow-light delay lines with 10^3 bits capacity?

Boyd, Gauthier, Gaeta, and Willner, Phys. Rev. A 71, 023801, 2005.

Generic Model of EIT and CPO Slow-Light Systems



probe absorption

$$\alpha(\delta) = \alpha_0 \left(1 - \frac{f}{1+\delta^2/\gamma^2}\right) \approx \alpha_0 \left[(1-f) - f\frac{\delta^2}{\gamma^2}\right] \quad \text{where} \quad \delta = \omega - \omega_0$$

probe refractive index (by Kramers Kronig)

$$n(\delta) = n_0 + f\left(\frac{\alpha_0 \lambda}{4\pi}\right)\frac{\delta/\gamma}{1+\delta^2/\gamma^2} \approx n_0 + f\left(\frac{\alpha_0 \lambda}{4\pi}\right)\frac{\delta}{\gamma}\left(1 - \frac{\delta^2}{\gamma^2}\right)$$

probe group index

$$n_g \approx f\left(\frac{\alpha_0 \lambda}{4\pi}\right)\frac{\omega}{\gamma}\left(1 - \frac{3\delta^2}{\gamma^2}\right).$$

induced delay

$$T_{\mathrm{del}} \approx \frac{f\alpha_0 L}{2\gamma}\left(1 - \frac{3\delta^2}{\gamma^2}\right)$$

normalized induced delay (T_0 = pulse width)

$$\frac{T_{\mathrm{del}}}{T_0} \approx \frac{f\alpha_0 L}{2\gamma T_0}\left(1 - \frac{3\delta^2}{\gamma^2}\right)$$

Limitations to Time Delay

Normalized induced delay

$$\frac{T_{\rm del}}{T_0} \approx \frac{f\alpha_0 L}{2\gamma T_0}\left(1 - \frac{3\delta^2}{\gamma^2}\right)$$

Limitation 1: Residual absorption limits L; Solution: Eliminate residual absorption

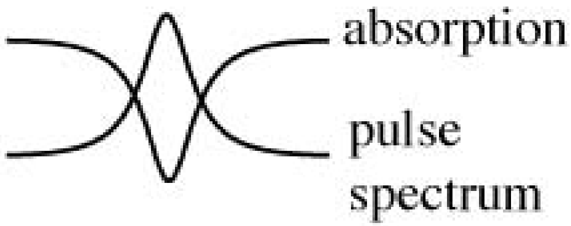
Limitation 2: Group velocity dispersion

A short pulse will have a broad spectrum and thus a range of values of δ
There will thus be a range of time delays, leading to a range of delays and pulse spreading
Insist that pulse not spread by more than a factor of 2. Thus

$$L_{\rm max} = 2\gamma^3 T_0^3/3f\alpha_0 \qquad \text{and} \qquad \left(\frac{T_{\rm del}}{T_0}\right)_{\rm max} = \frac{1}{3}\gamma^2 T_0^2.$$

Limitation 3: Spectral reshaping of pulse (more restrictive than limitation 2)

Pulse will narrow in frequency and spread in time
from T_0 to T where $T^2 = T_0^2 + f\alpha_0 L/\gamma^2$.



Thus

$$L_{\rm max} = 3T_0^2\gamma^2/(2f\alpha_0) \quad \text{and} \quad \left(\frac{T_{\rm del}}{T_0}\right)_{\rm max} = \frac{3}{2}\gamma T_0.$$

Note that γT_0 can be arbitrarily large!

Summary: Fundamental Limitations to Time Delay

- If one can eliminate residual absorption, the maximum relative time delay is

$$\left(\frac{T_{\rm del}}{T_0}\right)_{\rm max} = \frac{3}{2}\gamma T_0,$$

which has no upper bound.

- But to achieve this time delay, one needs a large initial (before saturation) optical depth given by

$$\alpha_0 L = (4/3)(T_{\rm del}/T_0)^2_{\rm max}.$$

- For typical telecommunications protocols, the bit rate B is approximately T_0^{-1} and the required transparency linewidth must exceed the bit rate by the relative delay

$$\gamma = \frac{2}{3} B \left(\frac{T_{\rm del}}{T_0}\right)_{\rm max}$$

Other Talks from My Group

MC6 • 3:15 p.m.
Room Temperature Slow Light with 17 GHz Bandwidth in Semiconductor Quantum Dots, *Giovanni Piredda, Aaron Schweinsberg, Robert W. Boyd; Inst. of Optics, USA.* We demonstrate the delay of a 25 ps pulse by 10% of its FWHM using coherent population oscillations in PbS quantum dots at room temperature. The 17 GHz bandwidth is adequate for telecommunications applications.

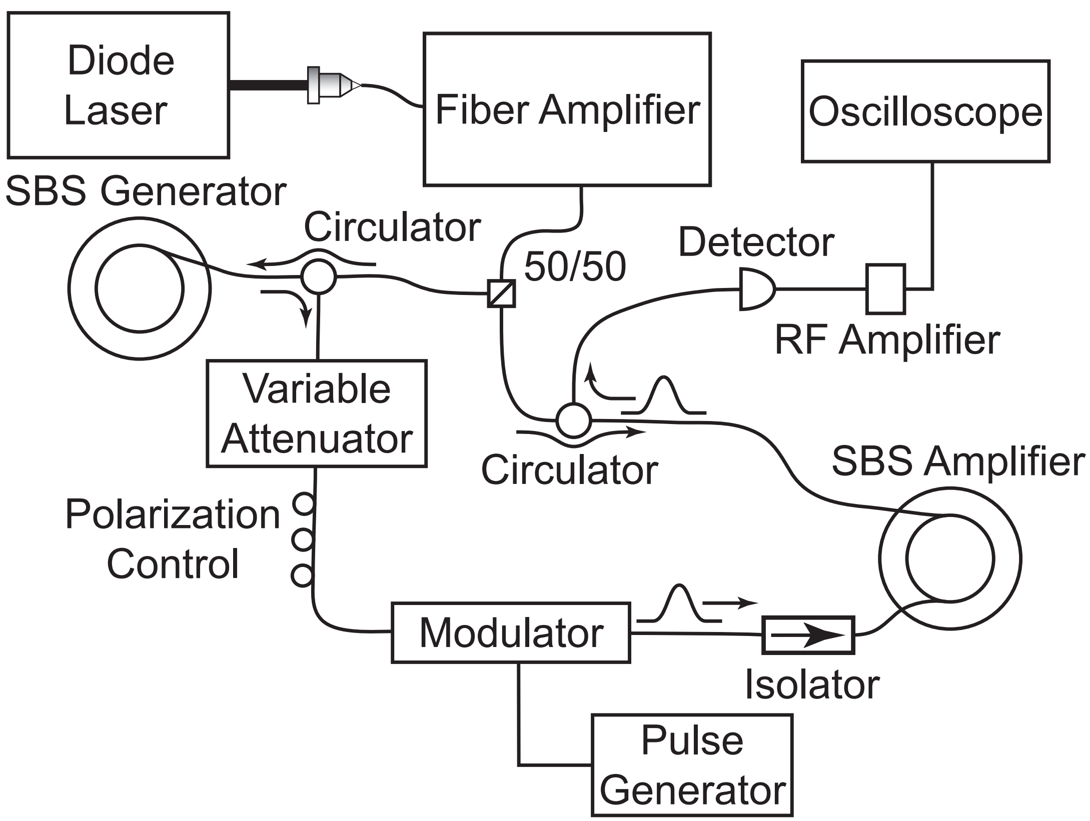
ME1• 6:00 p.m.
Slow Light with Gain Induced by Three Photon Effect in Strongly Driven Two-Level Atoms, *Yuping Chen[1,2], Zhimin Shi[1], Petros Zerom[1], Robert W. Boyd[1]; [1]Inst. of Optics, Univeristy of Rochester, USA, [2]Inst. of Optics and Photonics, Dept. of Physics, Shanghai Jiao Tong Univ., China.* Slow light induced by the three-photon effect is studied theoretically. The effect results from the modification of the atomic-level structure by the ac-Stark effect. A group index of the order of 106 can be obtained.

WA2 • 8:30 a.m.
Backwards Pulse Propagation with a Negative Group Velocity in Erbium Doped Fiber, *George M. Gehring, Aaron Schweinsberg, Robert W. Boyd; Inst. of Optics, Univ. of Rochester, USA.* Simple models predict that pulses propagate "backwards" through a material with a negative group velocity. We find that the peak of the pulse does propagate backwards, even though no energy propagates in that direction.

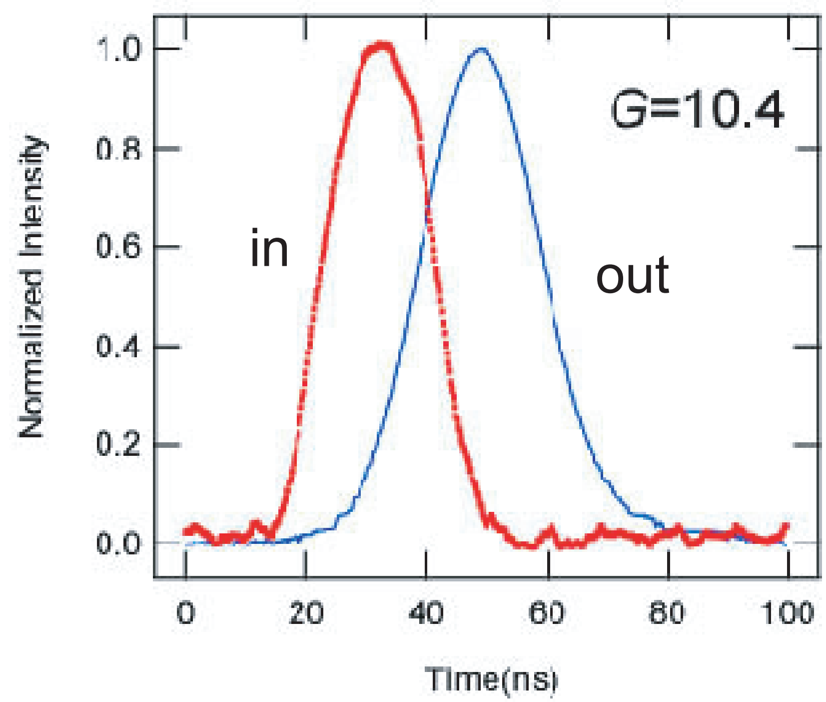
WB3 • 11:15 a.m.
Distortion-Reduced Pulse-Train Propagation with Large Delay in a Triple Gain Media, *Zhimin Shi[1], Robert W. Boyd[1], Zhaoming Zhu[2], Daniel J. Gauthier[2], Ravi Pant[3], Michael D. Stenner[3,4], Mark A. Neifeld[3,4]; [1]Inst. of Optics, Univ. of Rochester, USA, [2]Dept. of Physics, and Fitzpatrick Ctr. for Photonics and Communications Systems, Duke Univ., USA, [3]Optical Sciences Ctr., Univ. of Arizona, USA, [4]Dept. of Electrical and Computer Engineering, Univ. of Arizona, USA.* A slow light medium based on three closely spaced gain lines is studied. Both numerical calculations and experiments demonstrate that large delay can be achieved with large bandwidth and with very small distortion.

Slow-Light via Stimulated Brillouin Scattering

- Rapid spectral variation of the refractive response associated with SBS gain leads to slow light propagation
- Supports bandwidth of 100 MHz, large group delays
- Even faster modulation for SRS

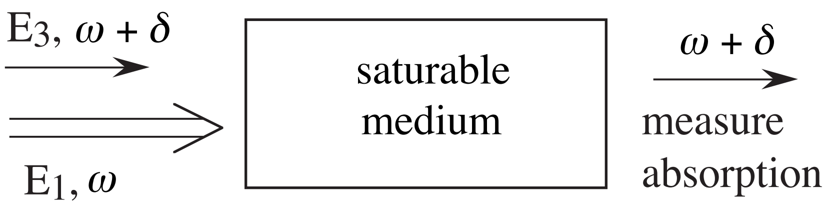


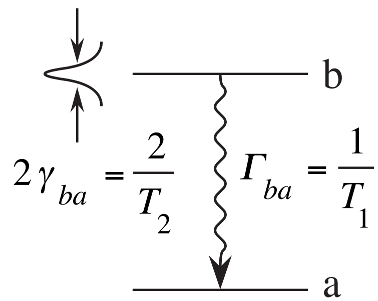
typical data

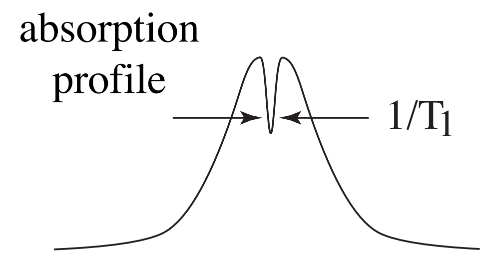


Okawachi, Bigelow, Sharping, Zhu, Schweinsberg, Gauthier, Boyd, and Gaeta Phys. Rev. Lett. 94, 153902 (2005).
Related results reported by Song, González Herráez and Thévenaz, Optics Express 13, 83 (2005).

Slow Light via Coherent Population Oscillations







- Ground state population oscillates at beat frequency δ (for $\delta < 1/T_1$).
- Population oscillations lead to decreased probe absorption (by explicit calculation), even though broadening is homogeneous.
- Rapid spectral variation of refractive index associated with spectral hole leads to large group index.
- Ultra-slow light ($n_g > 10^6$) observed in ruby and ultra-fast light ($n_g = -4 \times 10^5$) observed in alexandrite by this process.
- Slow and fast light effects occur at room temperature!

PRL 90,113903(2003); Science, 301, 200 (2003)

Advantages of Coherent Population Oscillations for Slow Light

Works in solids

Works at room temperature

Insensitive of dephasing processes

Laser need not be frequency stabilized

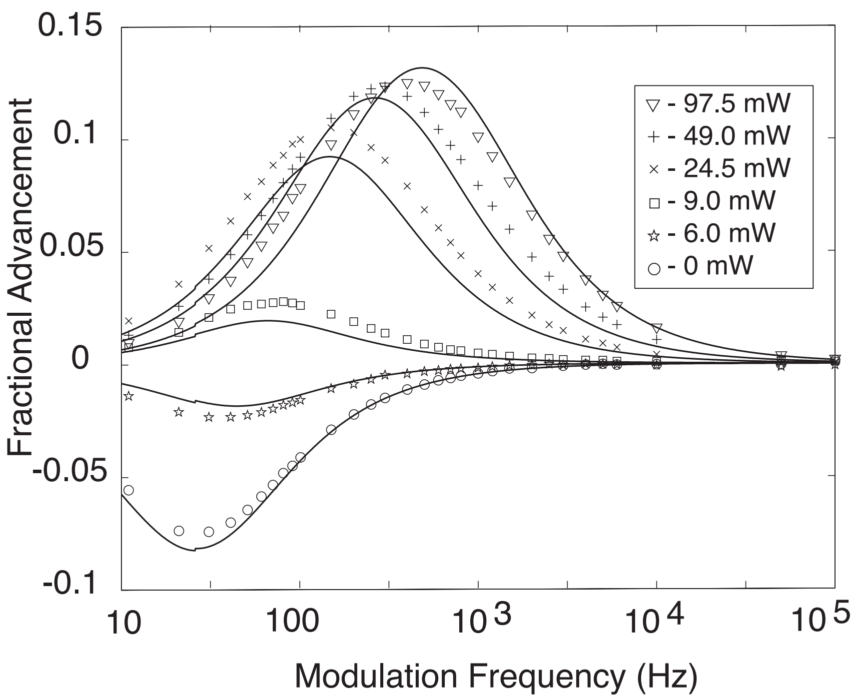
Works with single beam (self-delayed)

Delay can be controlled through input intensity

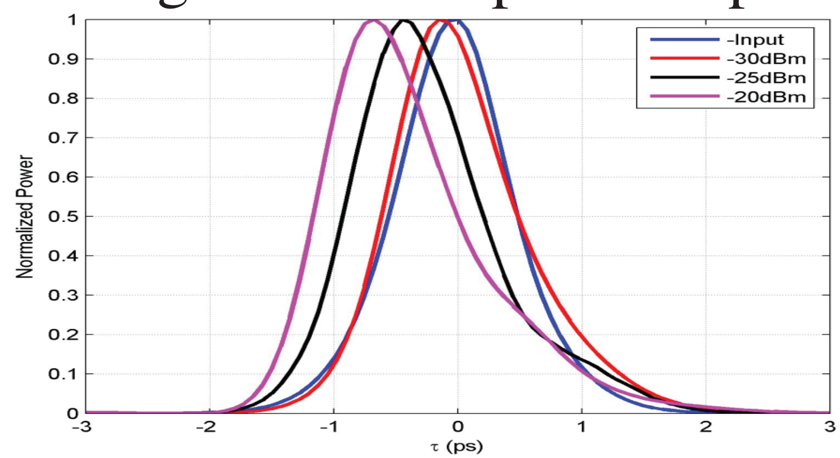
Slow Light via Coherent Population Oscillations

- Ultra-slow light ($n_g > 10^6$) observed in ruby and ultra-fast light ($n_g = -4 \times 10^5$) observed in alexandrite at room temperature.

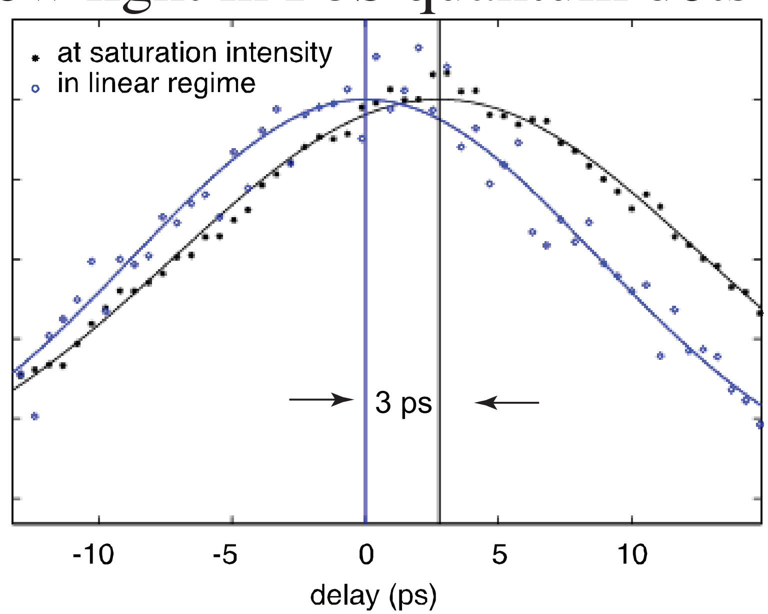
- Slow and fast light in an EDFA



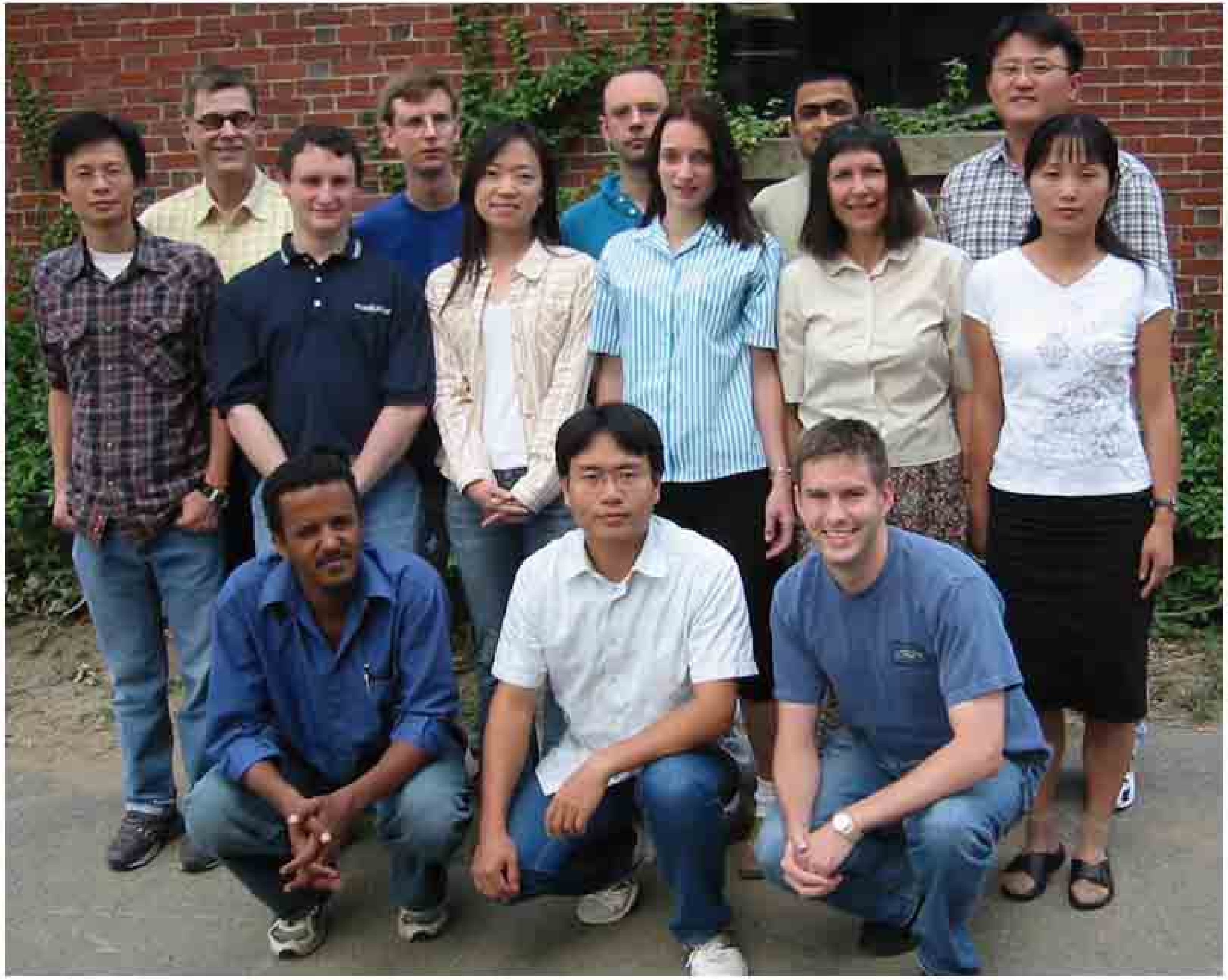
- Slow light in a SC optical amplifier



- Slow light in PbS quantum dots



Special Thanks to My Students and Research Associates



Thank you for your attention!

And thanks to NSF and DARPA for financial support!

Our results are posted on the web at:

http://www.optics.rochester.edu/~boyd

Physics is all about asking the right questions

Just ask

Evelyn **Hu**

Watt Webb (or James **Watt**)

Michael **Ware**

Wen I Wang

Kam **Wai** Chan

Not to mention

Lene **Hau**