Slowing Down the Speed of Light

Applications of "Slow" and "Fast" Light

Robert W. Boyd

Institute of Optics and
Department of Physics and Astronomy
University of Rochester

Presented at Louisiana State University, April 6, 2006.

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

And what about fast light ($v > c$ or negative)?

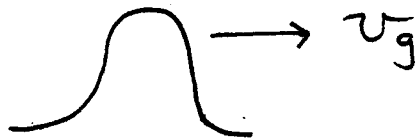
Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.

Outline of the Presentation

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

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

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

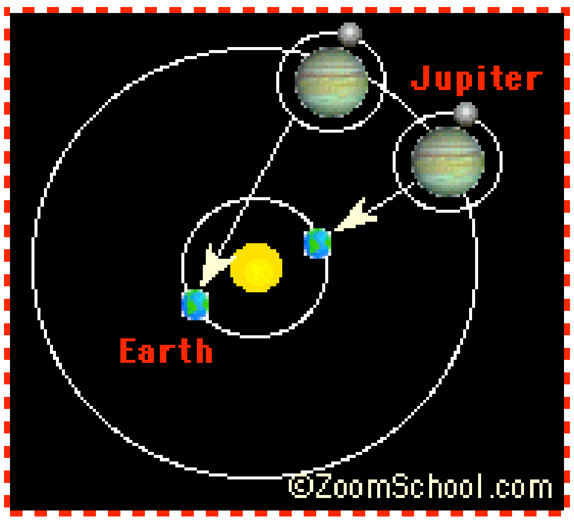
Thus $n_g \neq n$ in a dispersive medium!

Switch to Overheads

Determination of the Velocity of Light*
"Astronomical" Methods

Römer (1676) First evidence that velocity of light is finite!

Observed an apparent variation of up to 22 minutes in the orbital period of the satellite Io in its orbit about Jupiter.



Deduced that c = 225,000 km/sec

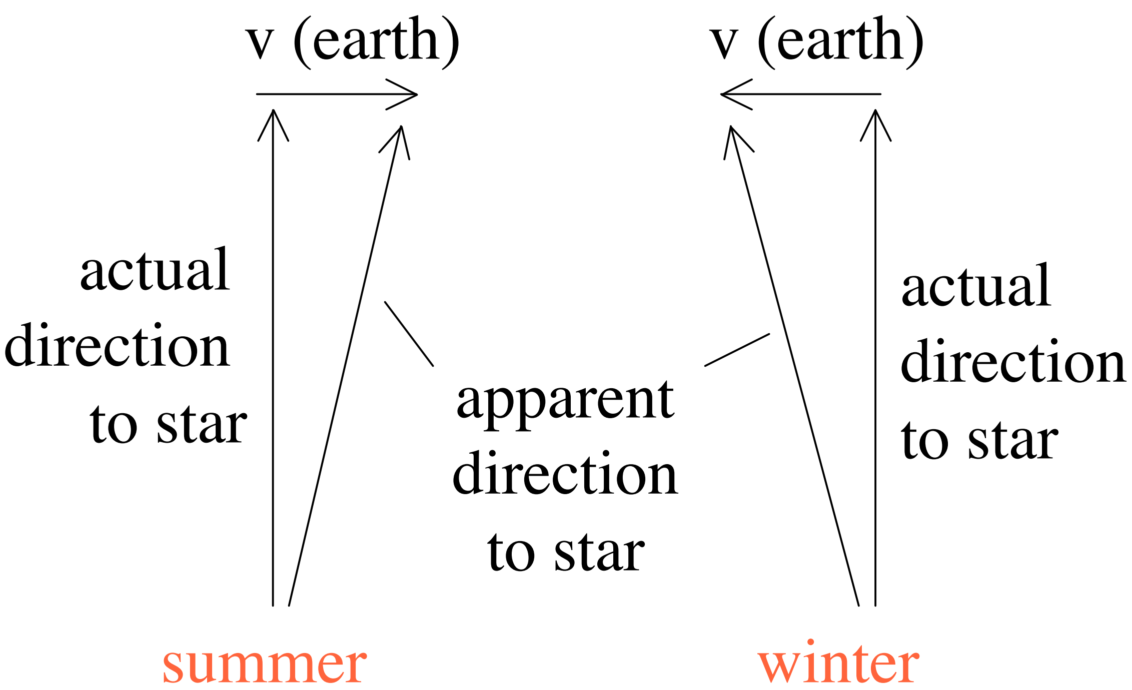
(Actually, light transit time from sun to earth is just over 8 minutes, and c = 299,793 km/sec)

*See, for instance, Jenkins and White, 1976.

Determination of the Velocity of Light
Astronomical Methods

Bradley (1727); Aberration of star light.

Confirmation of the finite velocity of light.



$$v(\text{earth}) \approx 30 \text{ km/s}$$

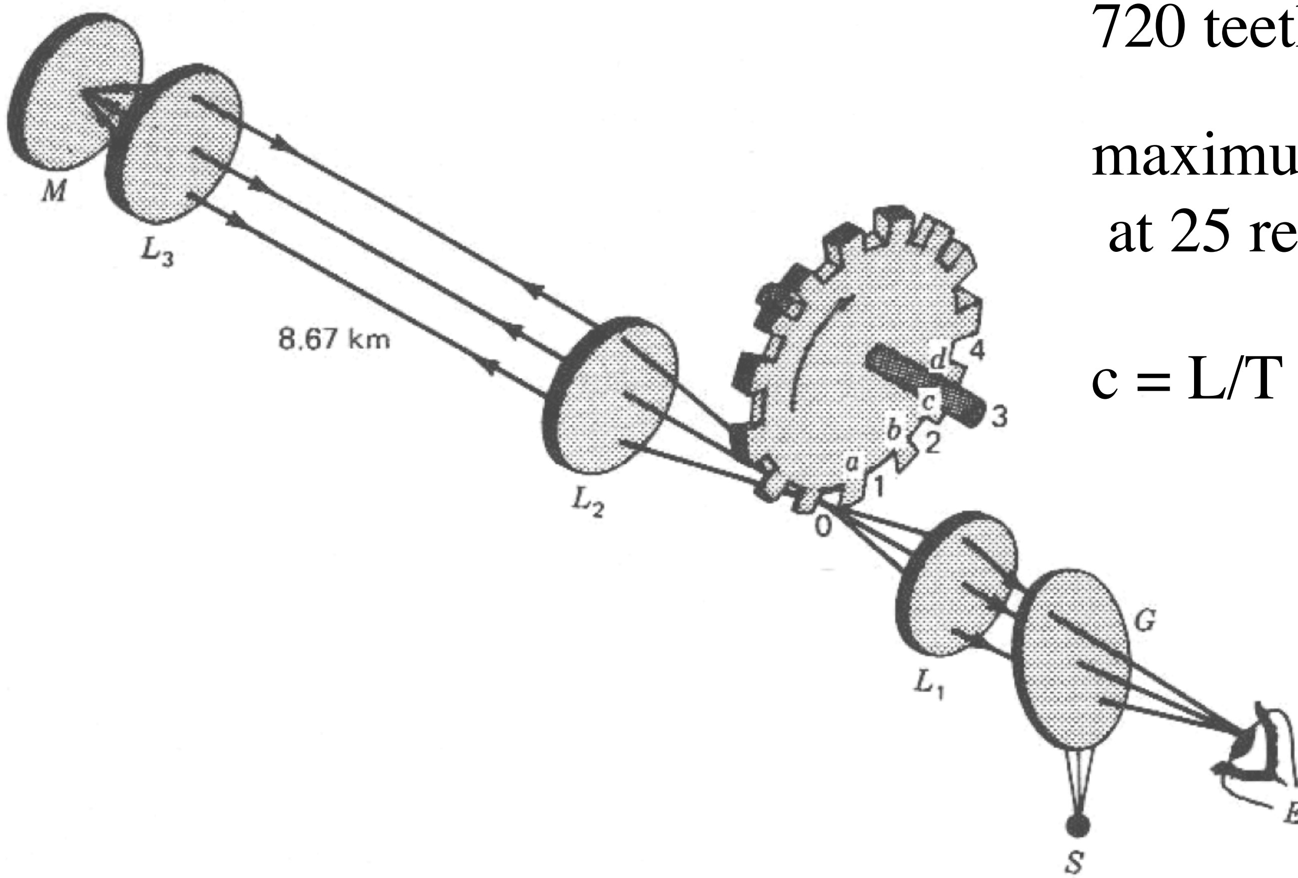
$$\tan\alpha = \frac{v(\text{earth})}{c}$$

$$\alpha = 20.5 \text{ arcsec}$$

Determination of the Velocity of Light

Laboratory Methods

Fizeau (1849) Time-of-flight method



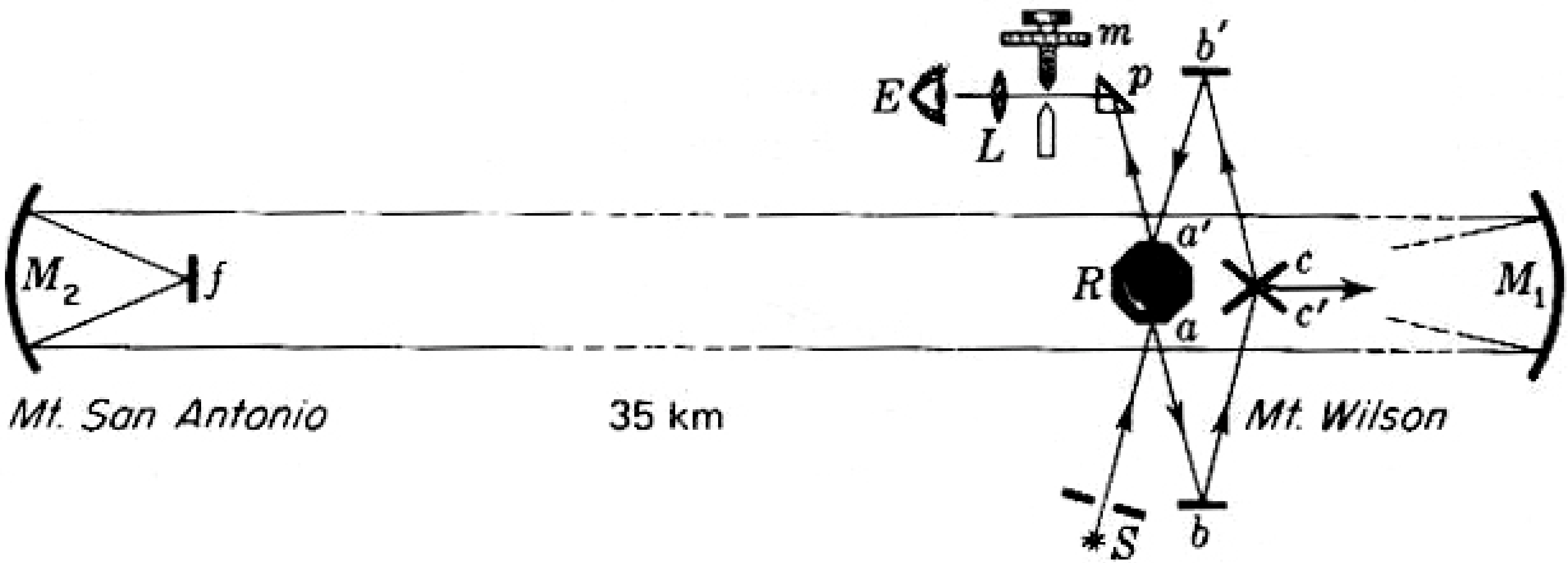
720 teeth in wheel

maximum transmission
at 25 revolutions/sec

$c = L/T = 320{,}000$ km/s

Determination of the Velocity of Light
Laboratory Methods

Michelson (1926); Improved time of flight method.



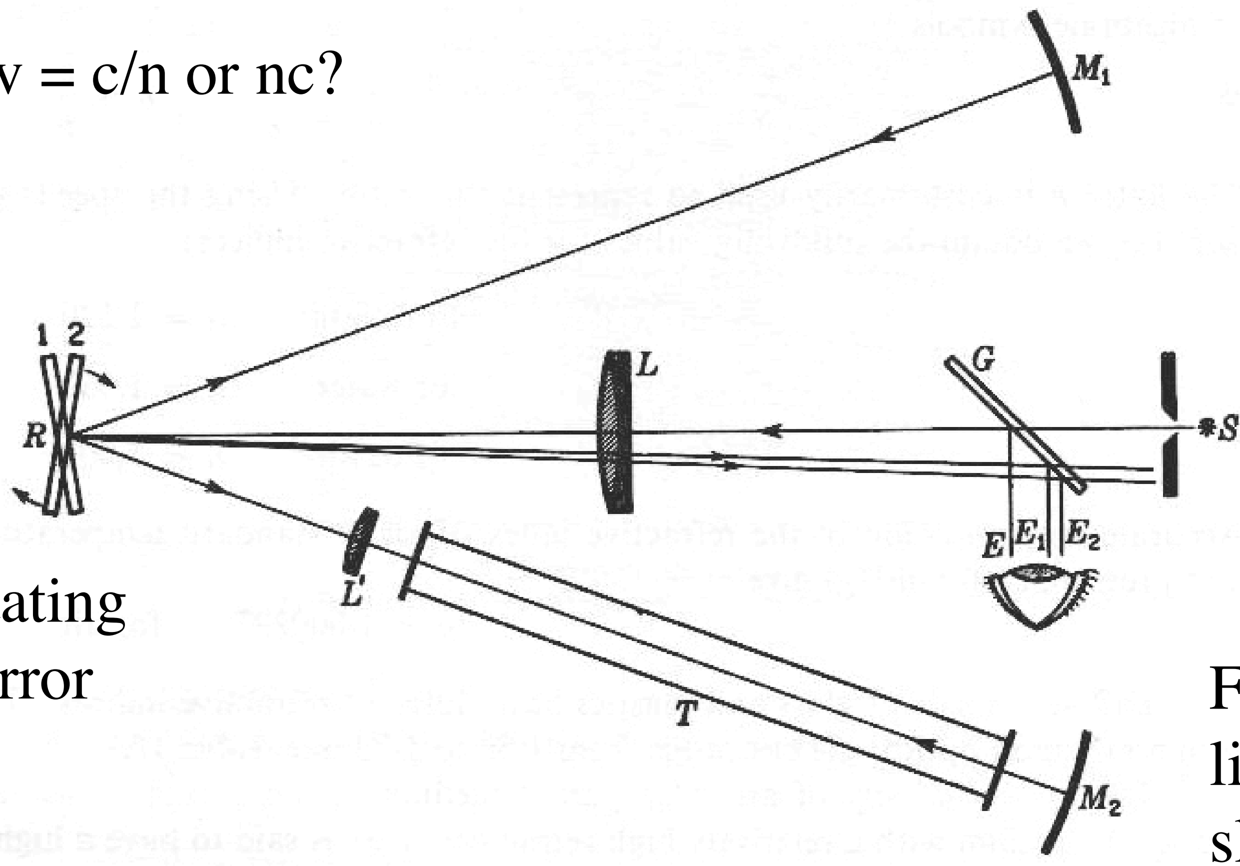
Rotating octagonal mirror

c = 299,296 km/s (or 299,298 km/s)

Velocity of Light in Matter

Foucault (1850) Velocity of light in water.

Is v = c/n or nc?



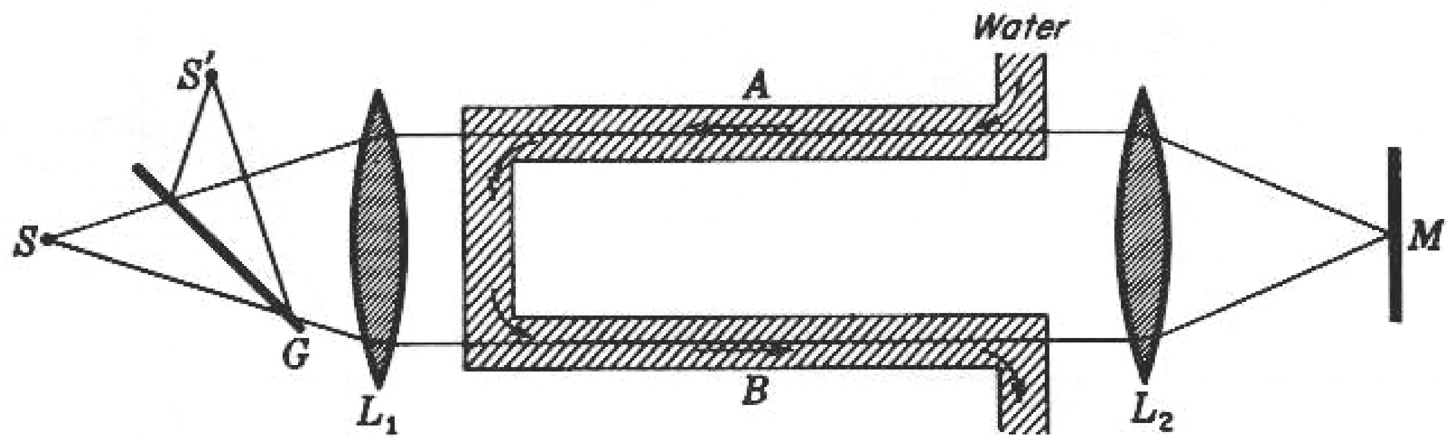
rotating mirror

Foucault finds that light travels more slowly in water!

Velocity of Light in Moving Matter

Fizeau (1859); Velocity of light in flowing water.

V = 700 cm/sec; L = 150 cm; displacement of 0.5 fringe.



Modern theory: relativistic addition of velocities

$$\mathrm{v} = \frac{\mathrm{c}/n + V}{1 + (V/\mathrm{c})(1/n)} \approx \frac{c}{n} + V\left(1 - \frac{1}{n^2}\right)$$

Fresnel "drag" coefficient

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

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

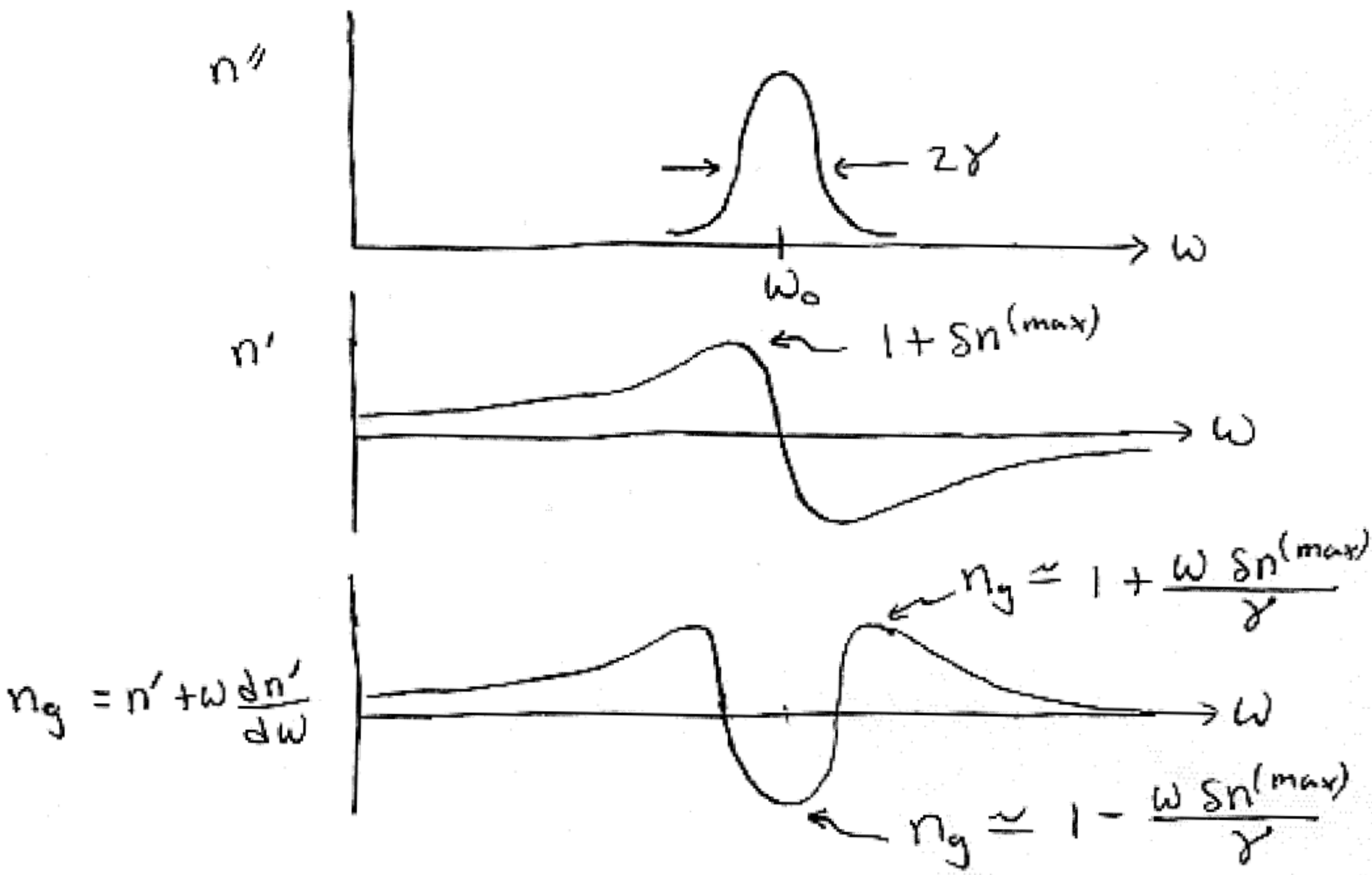
Light Propagation in Atomic Vapors

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

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

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

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



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

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

(But with lots of absorption)

How to Produce Slow Light?

Group index can be as large as

$$n_g \simeq 1 + \frac{\omega \, \delta n^{(max)}}{\gamma}$$

Use nonlinear optics to

(1) decrease line width γ

(produce sub-Doppler linewidth)

(2) decrease absorption

(so transmitted pulse is detectable)

Slow Light in Atomic Vapors

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

Hau and Harris

Welch and Scully

Budker

and others

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

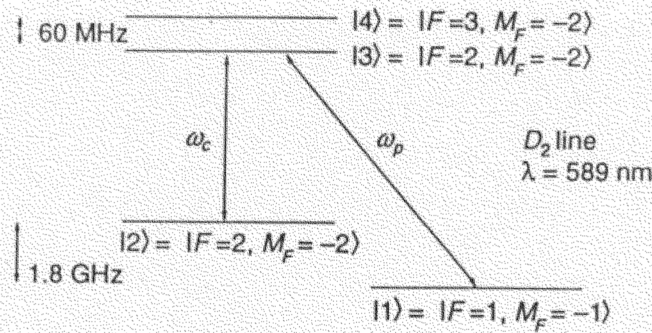
Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§

* *Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142, USA*

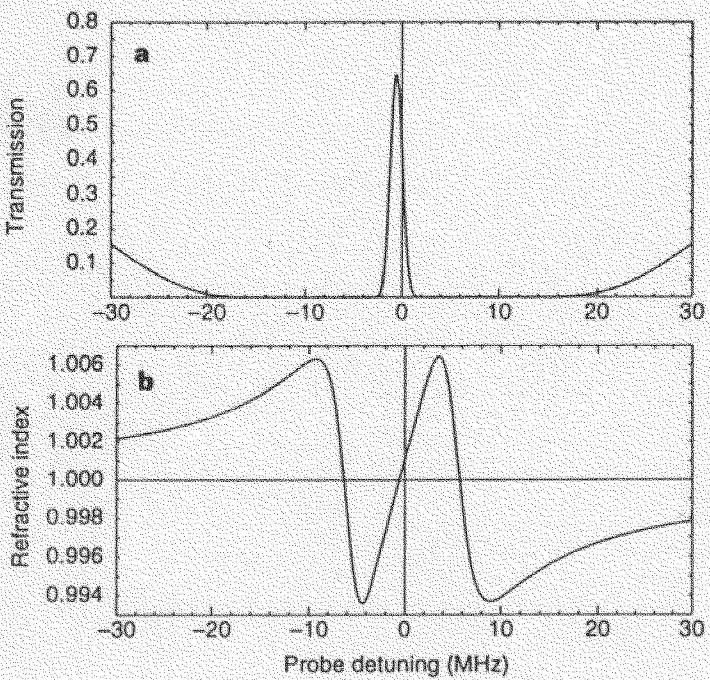
† *Department of Physics,* § *Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*

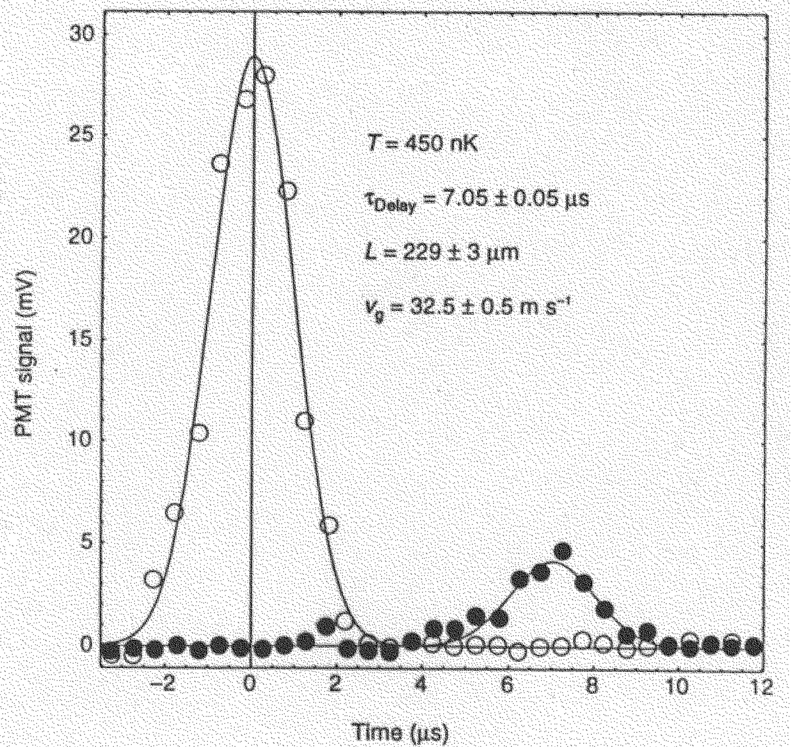
‡ *Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

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

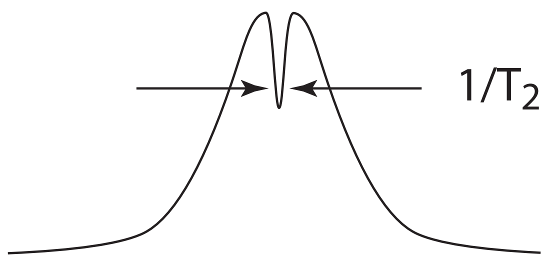
Recall that $n_g = n + \omega(dn/d\omega)$. Need a large $dn/d\omega$. (How?)

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

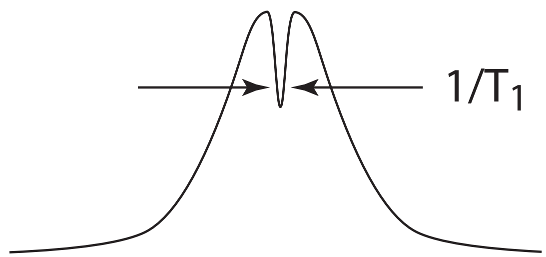
Well-known "trick" for doing so:

Make use of spectral holes due to population oscillations.

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



inhomogeneously broadened medium

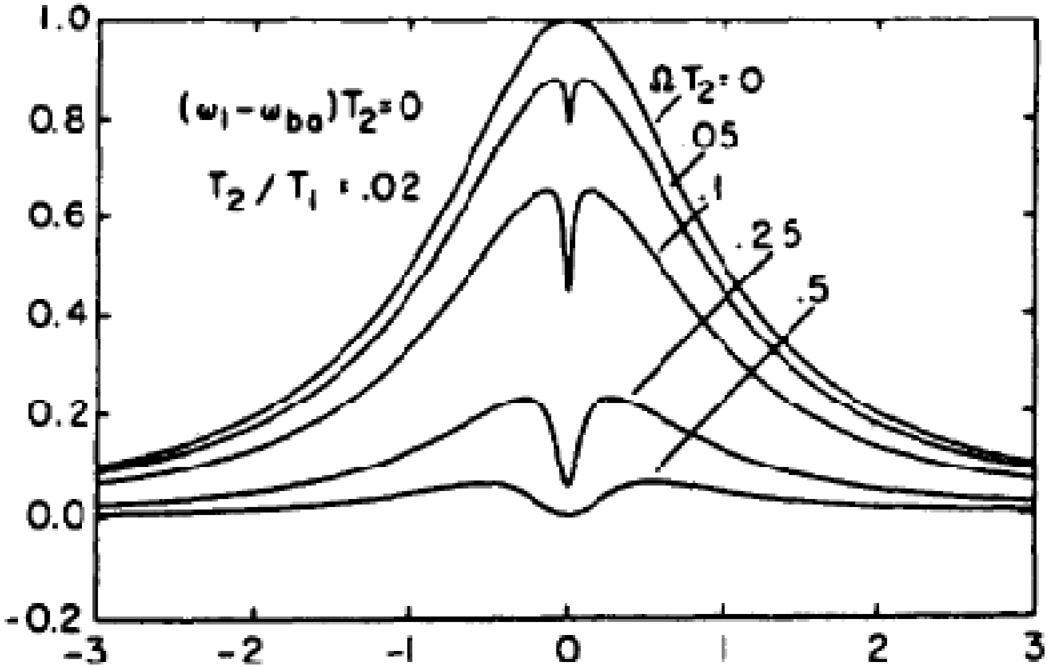


homogeneously broadened medium (or inhomogeneously broadened)

PRL 90,113903(2003).

Spectral Holes in Homogeneously Broadened Materials

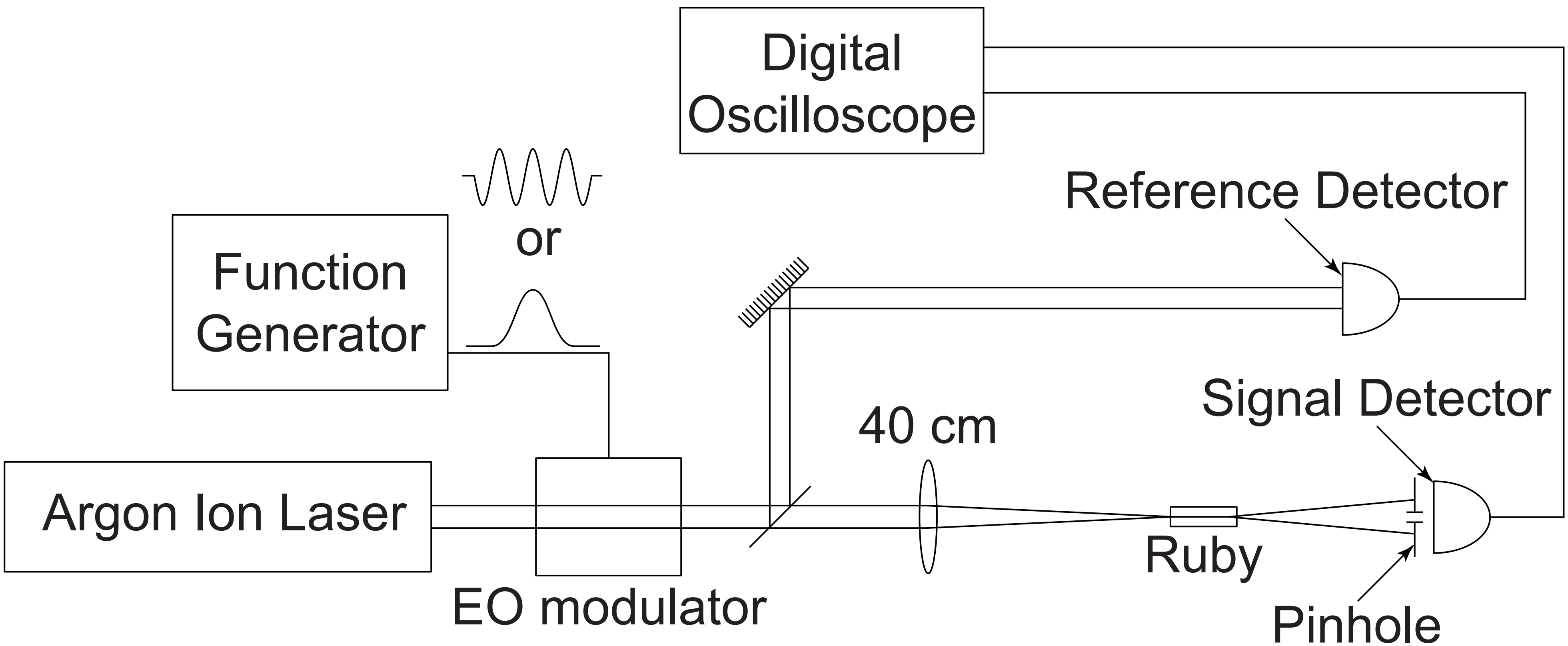
Occurs only in collisionally broadened media ($T_2 << T_1$)



pump-probe detuning (units of $1/T_2$)

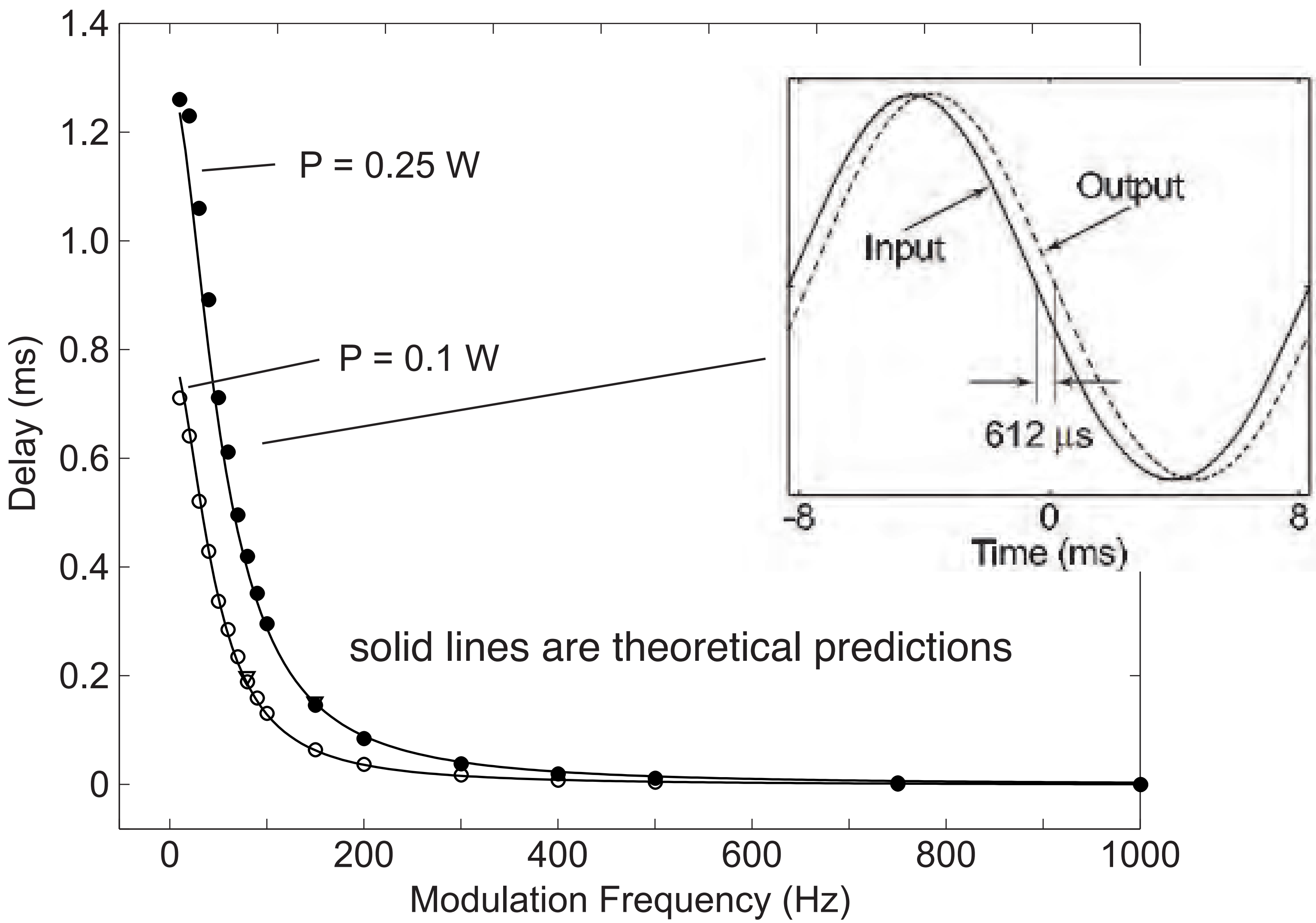
Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

Slow Light Experimental Setup



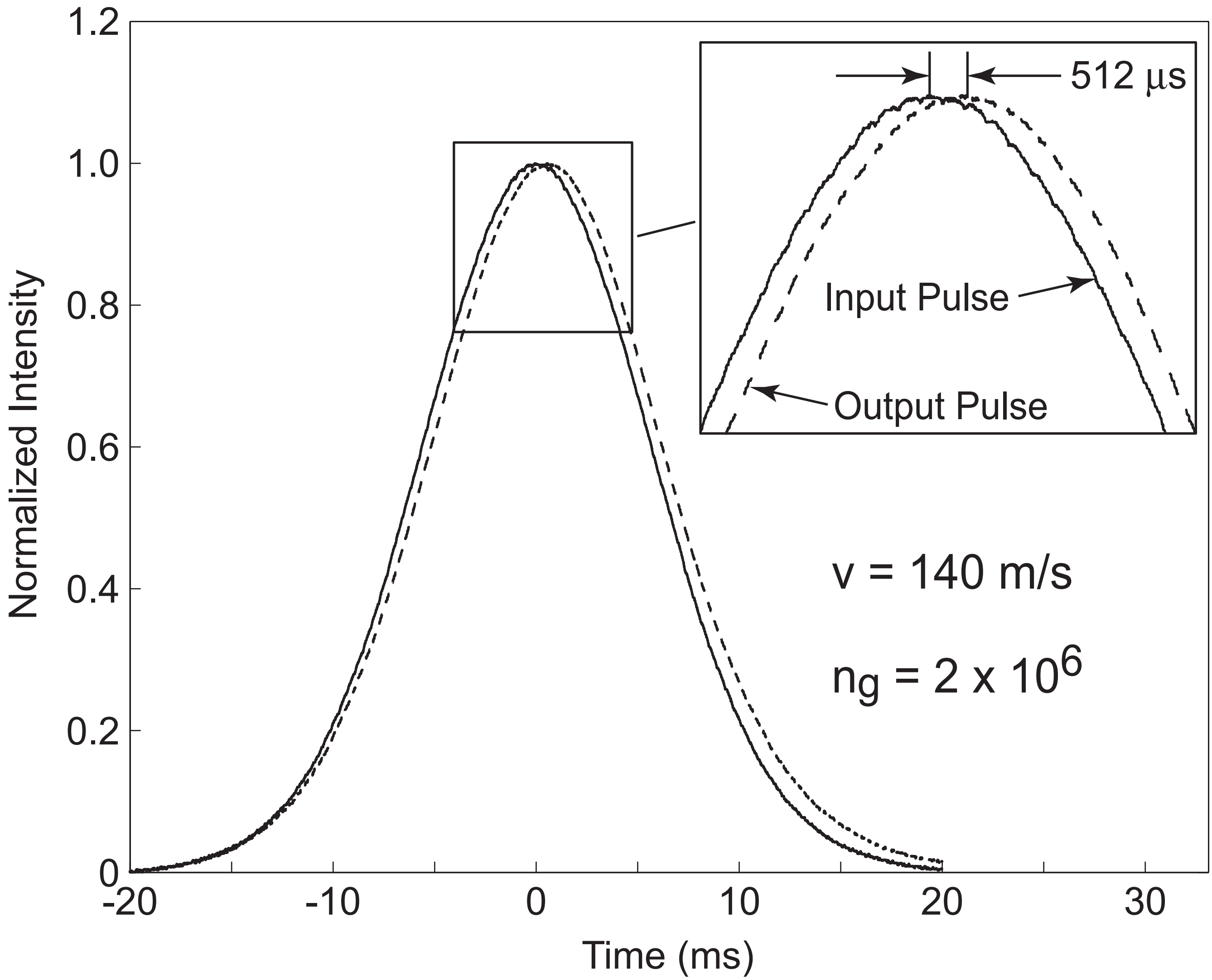
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



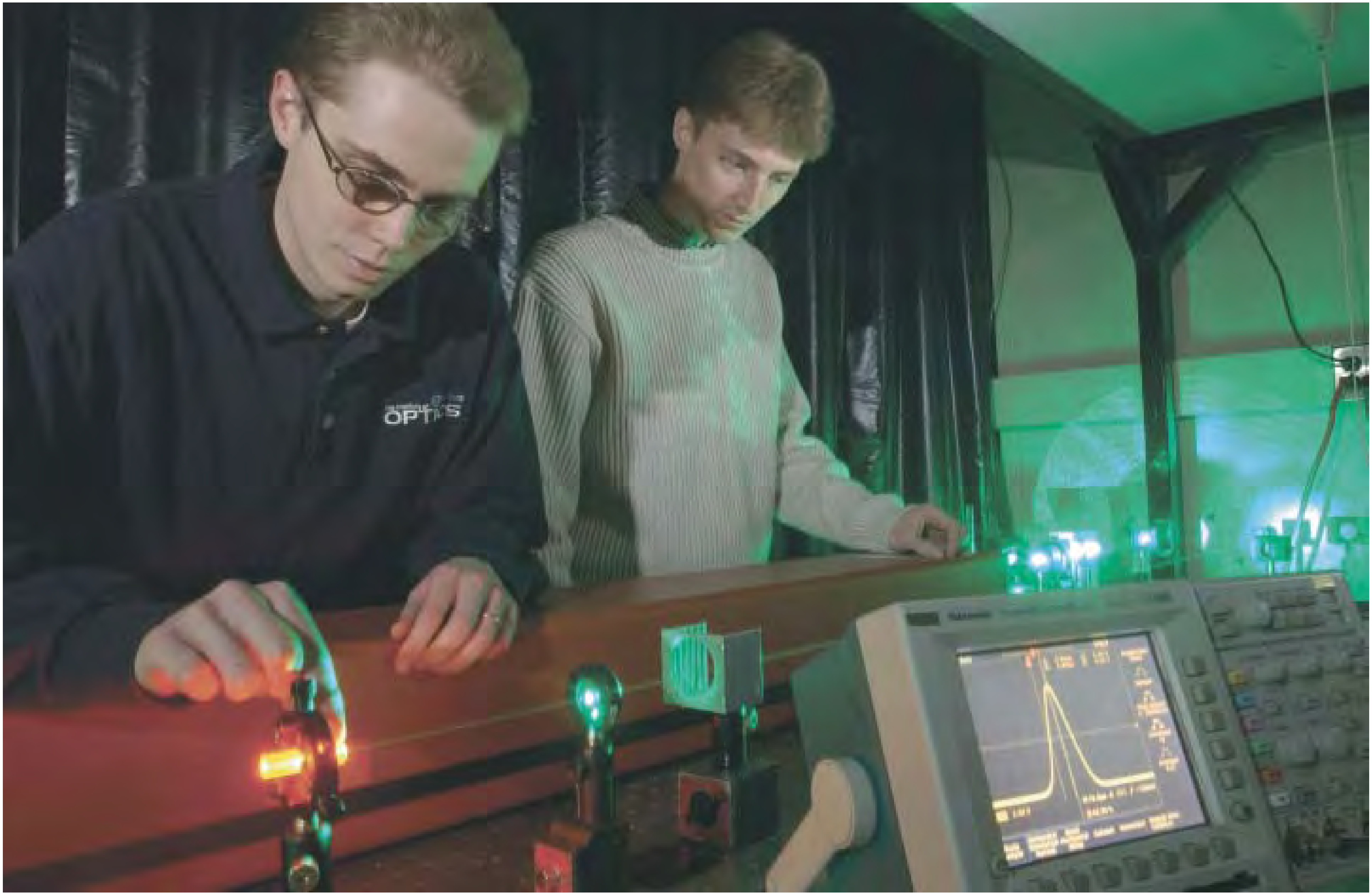
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

Gaussian Pulse Propagation Through Ruby



No pulse distortion!

Matt Bigelow and Nick Lepeshkin in the Lab



Advantages of Coherent Population Oscillations for Slow Light

Works in solids

Works at room temperature

Insensitive of dephasing processes

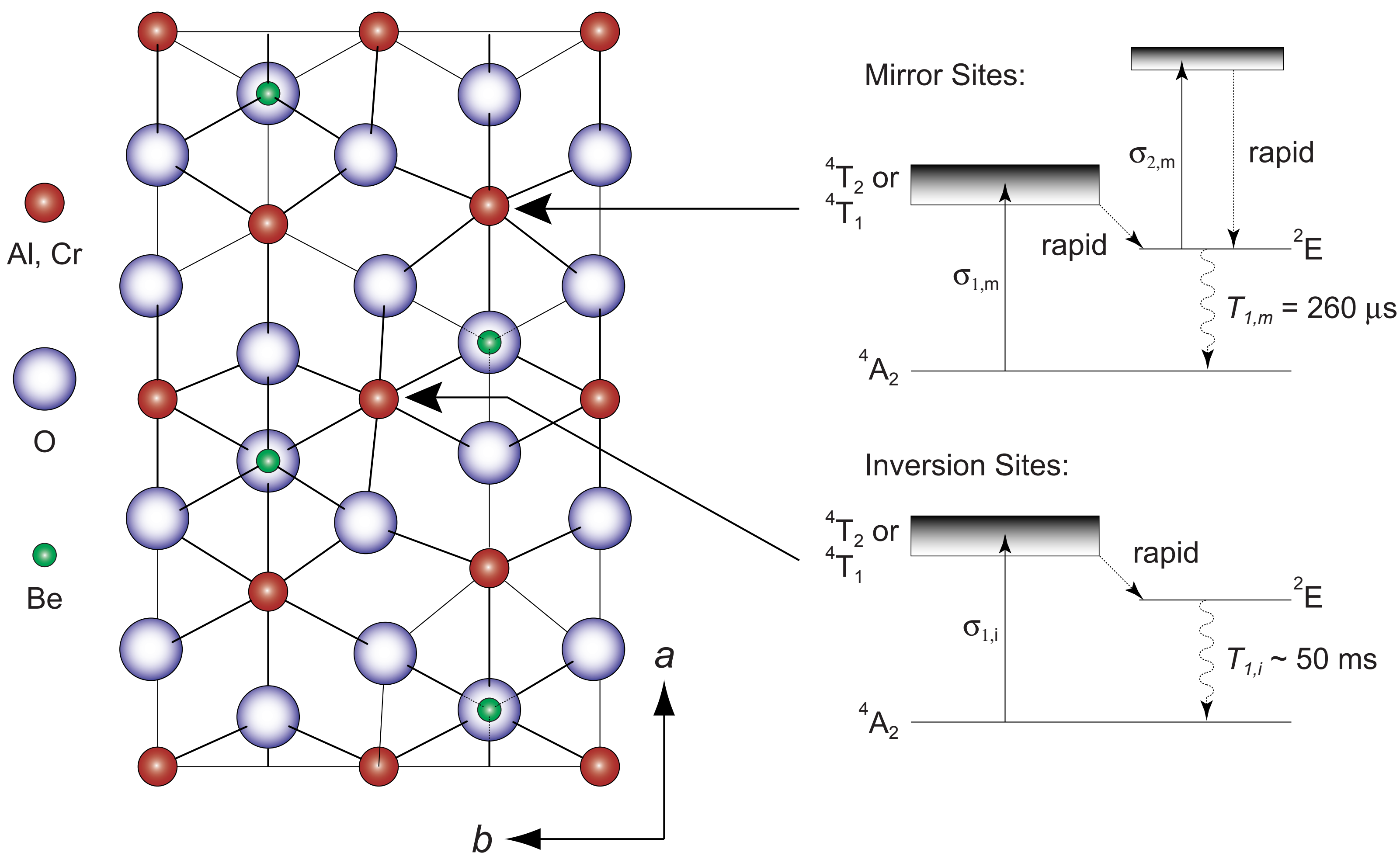
Laser need not be frequency stabilized

Works with single beam (self-delayed)

Delay can be controlled through input intensity

Alexandrite Displays both Saturable and Reverse-Saturable Absorption

- Both slow and fast propagation observed in alexandrite

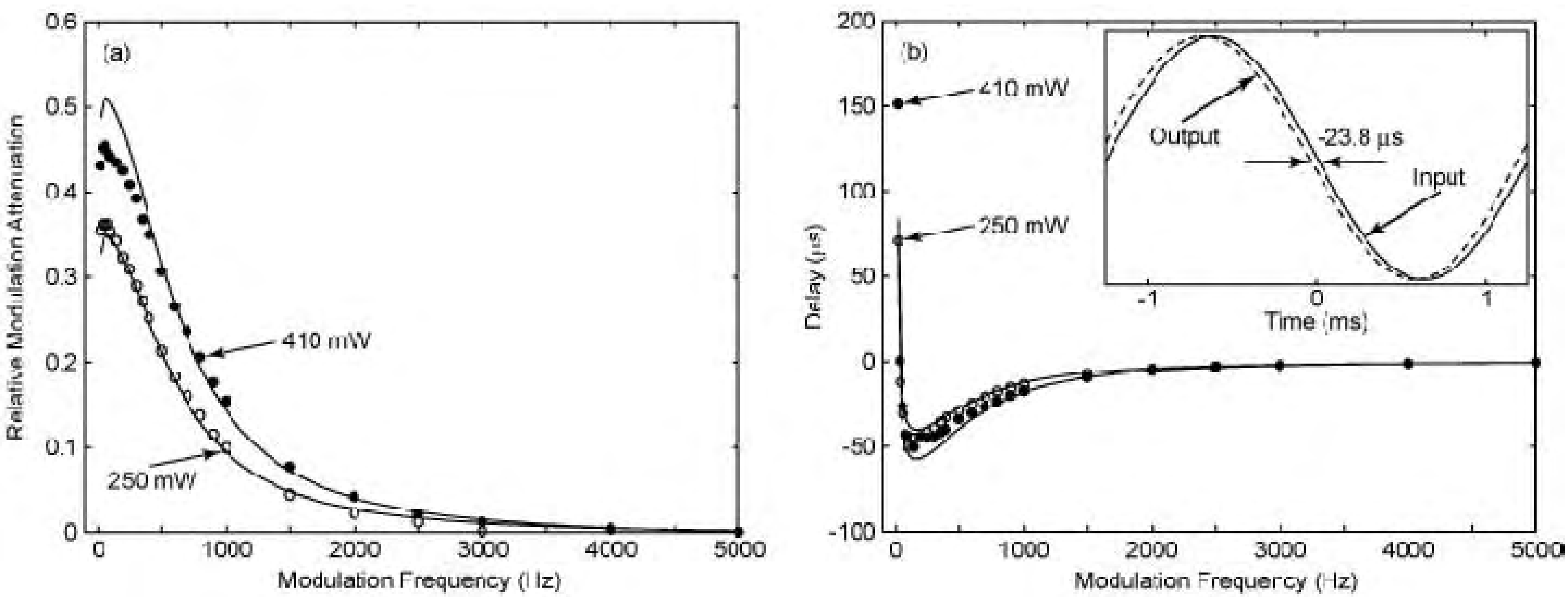


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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.

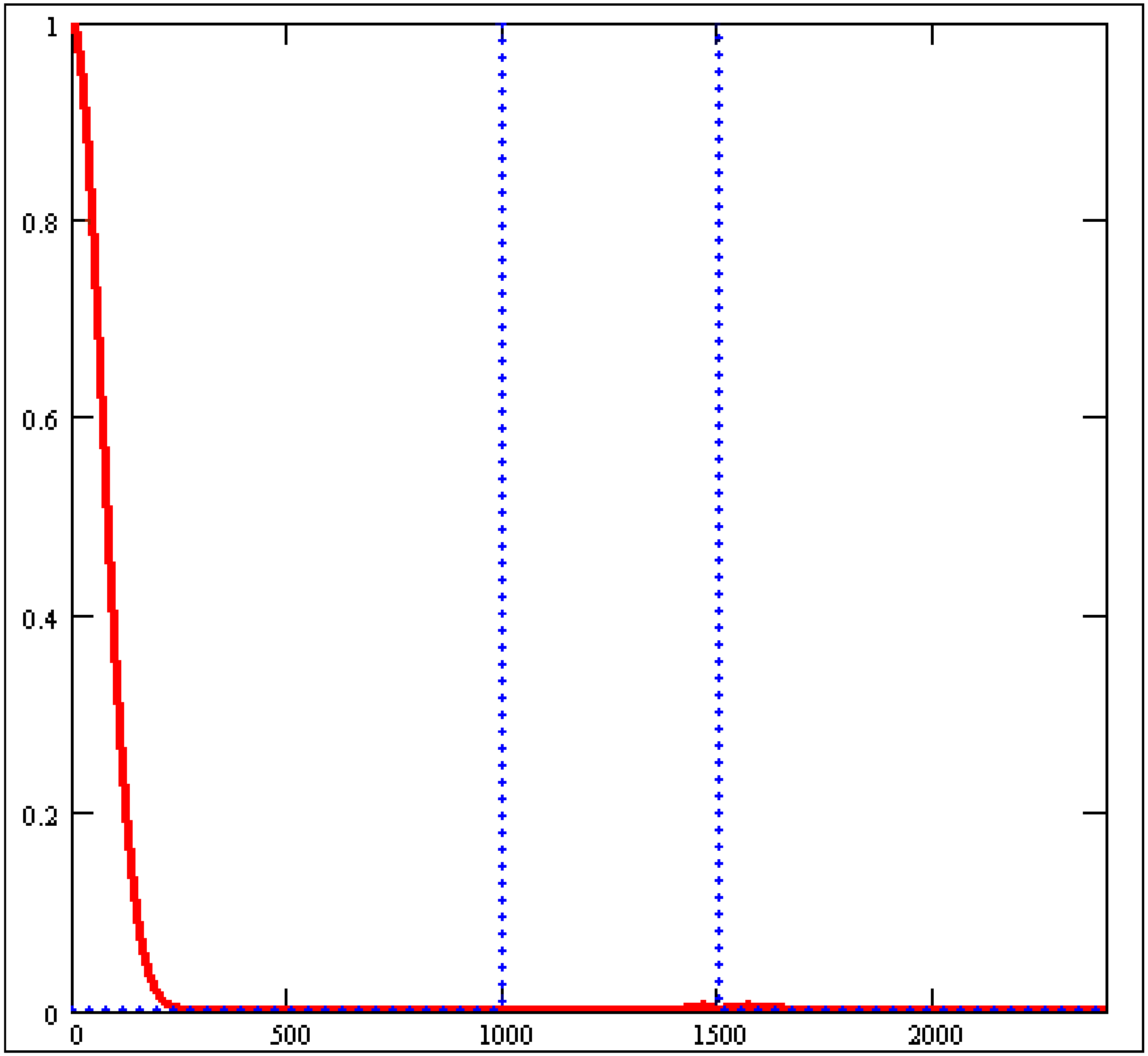
Assume an input pulse with a Gaussian temporal profile.

Study three cases:

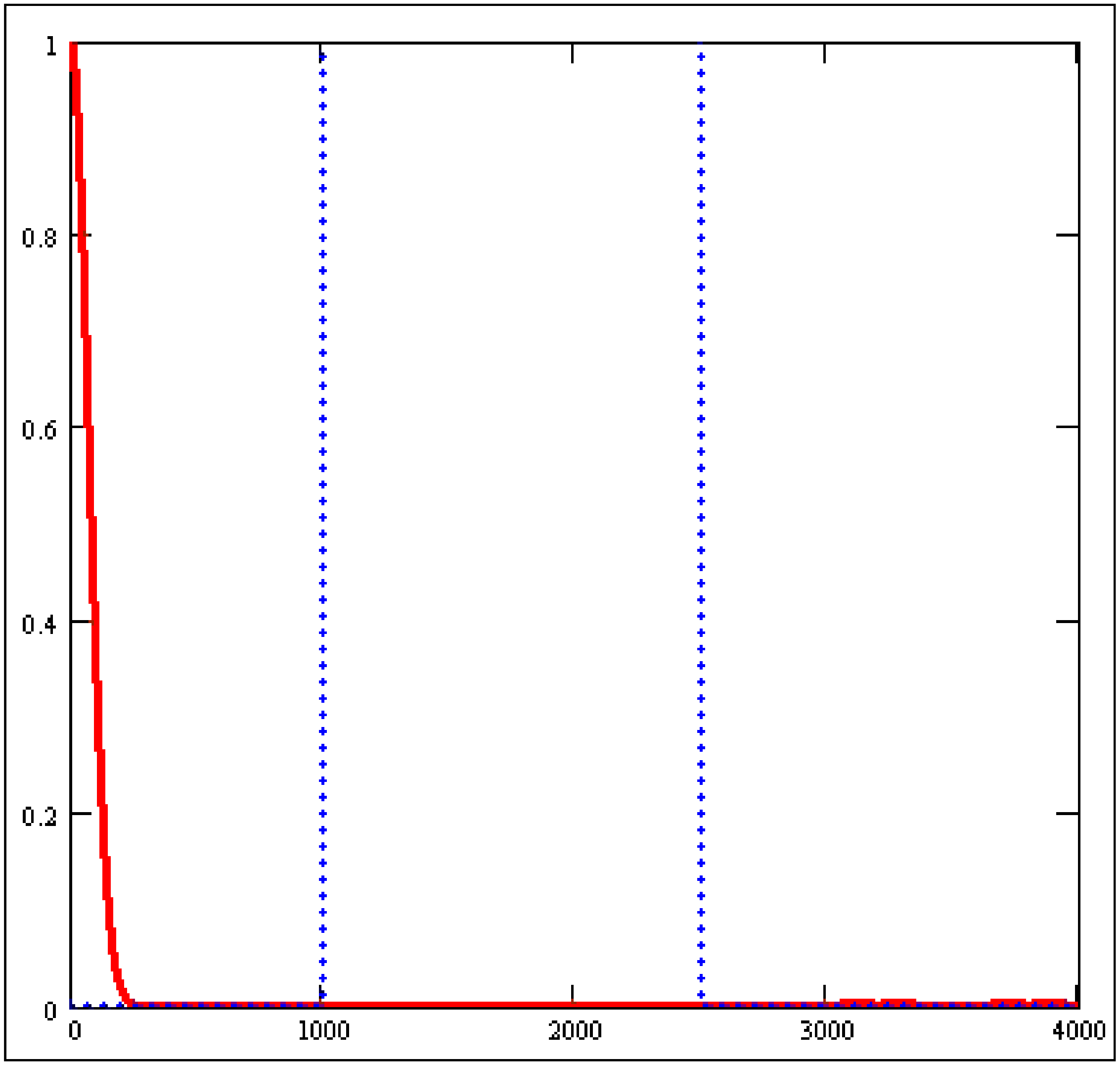
Slow light $v_g = 0.5$ c

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

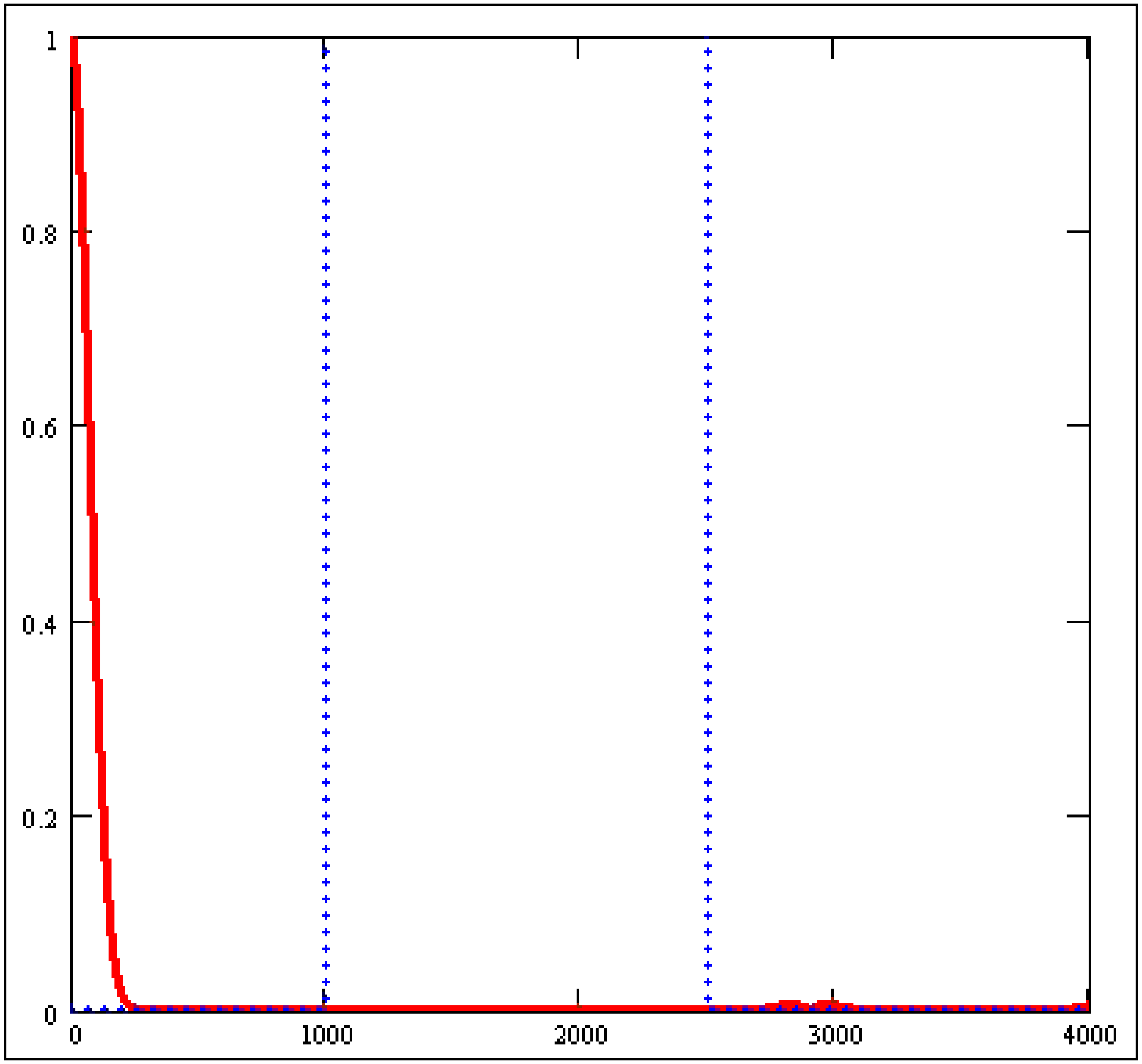
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



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

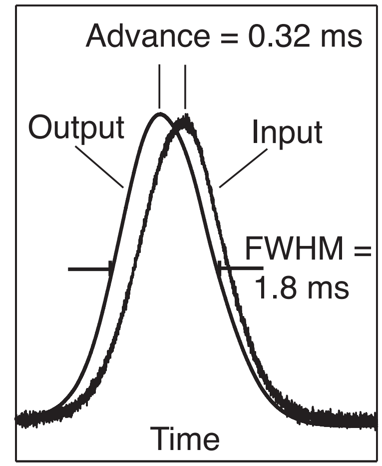


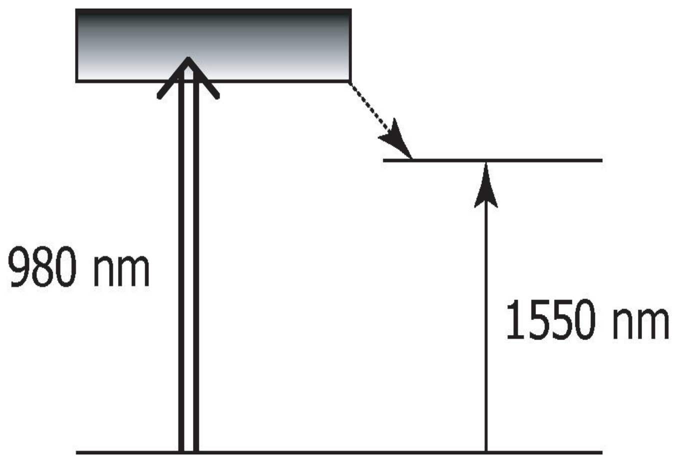
Pulse Propagation through a Fast-Light Medium (n_g = -.5, v_g = -2 c)

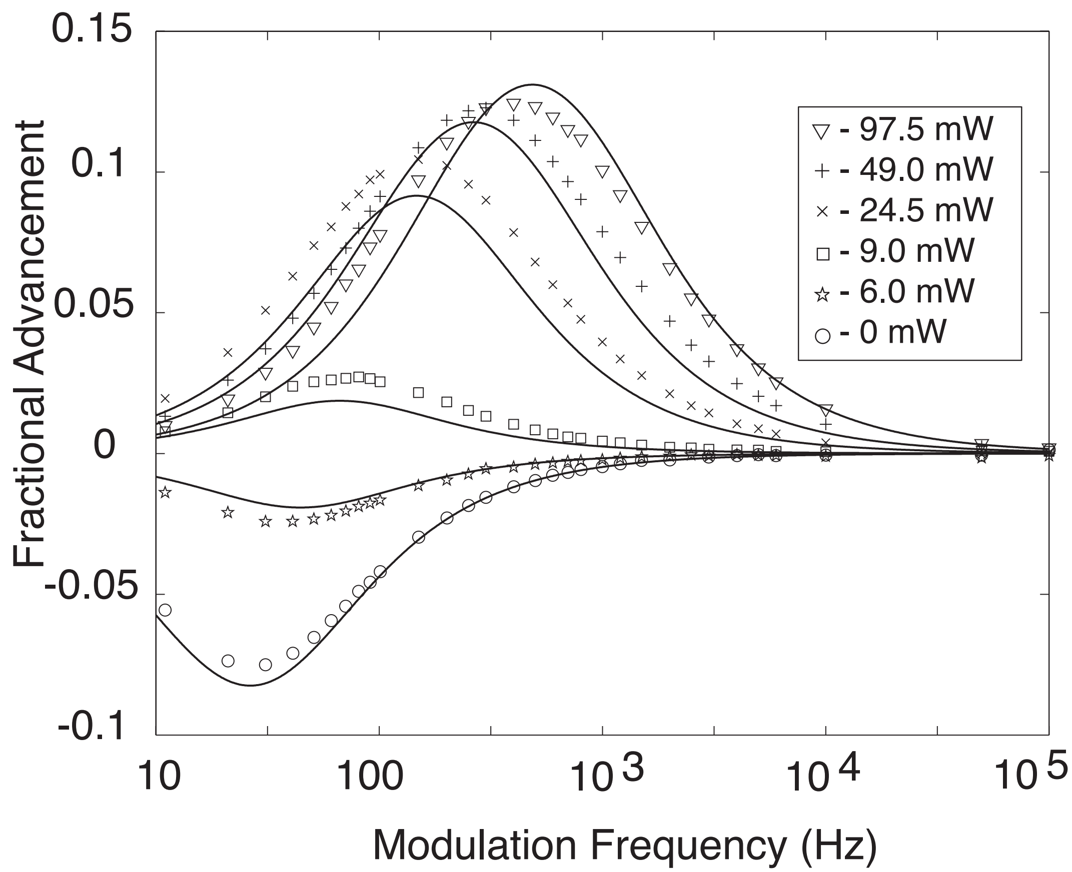


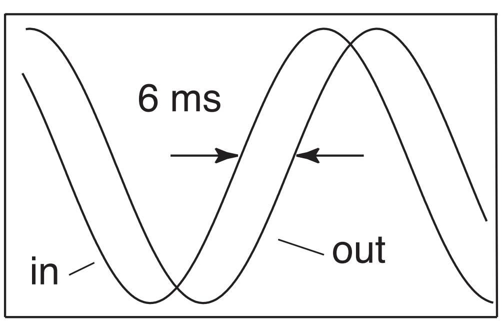
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



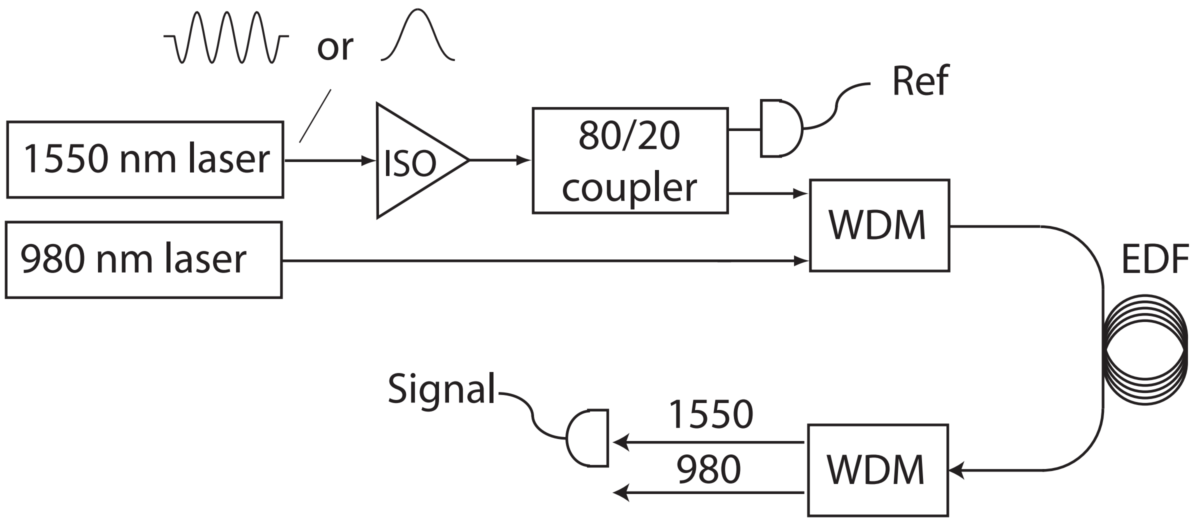






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo

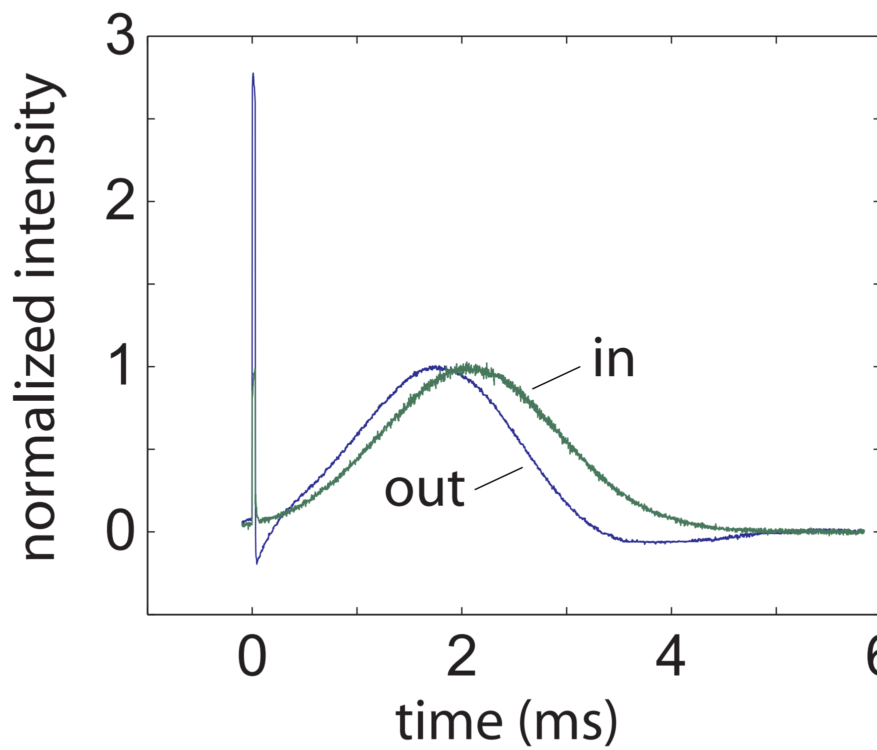
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



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

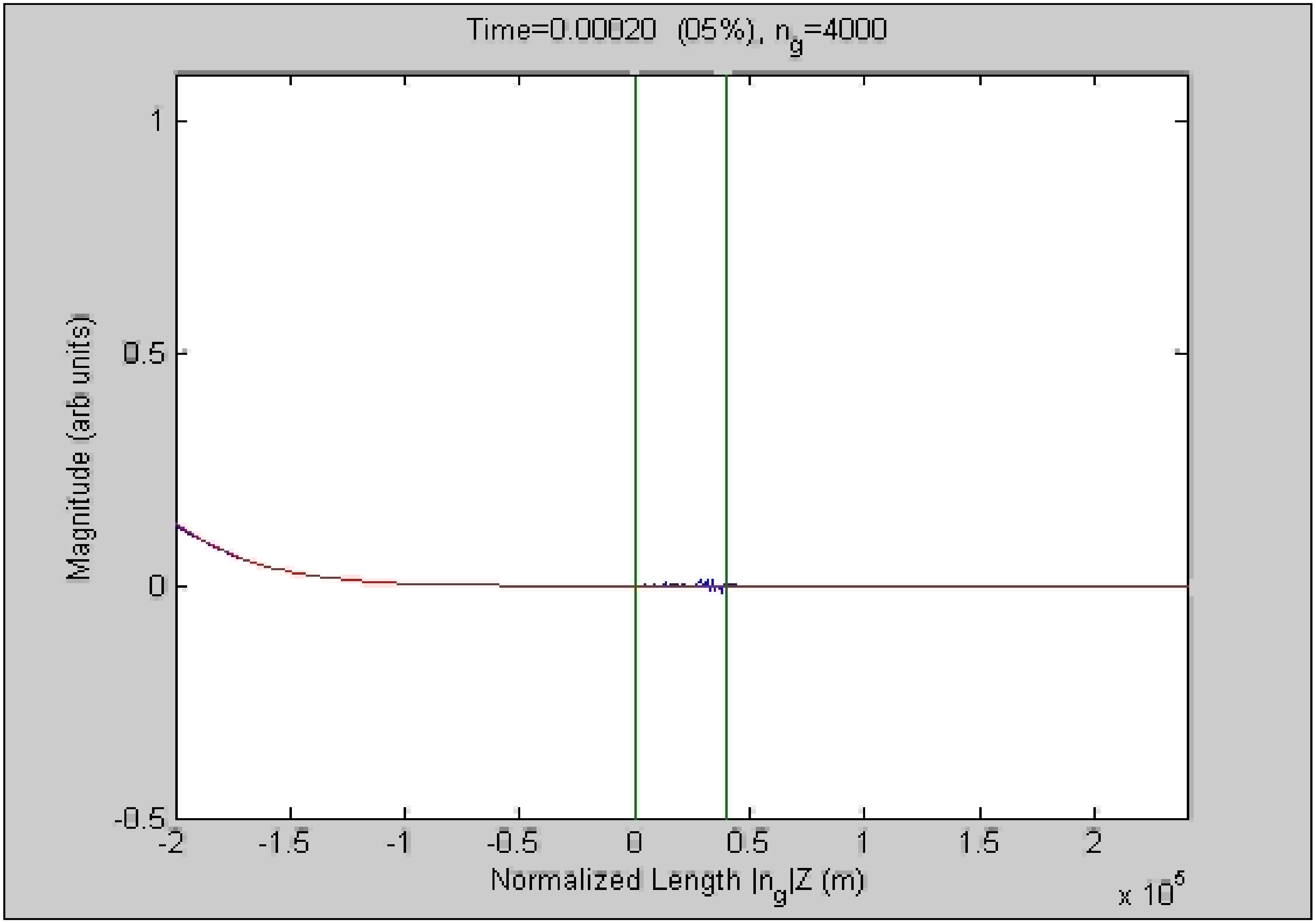
Procedure

- cutback method
- couplers embedded in fiber



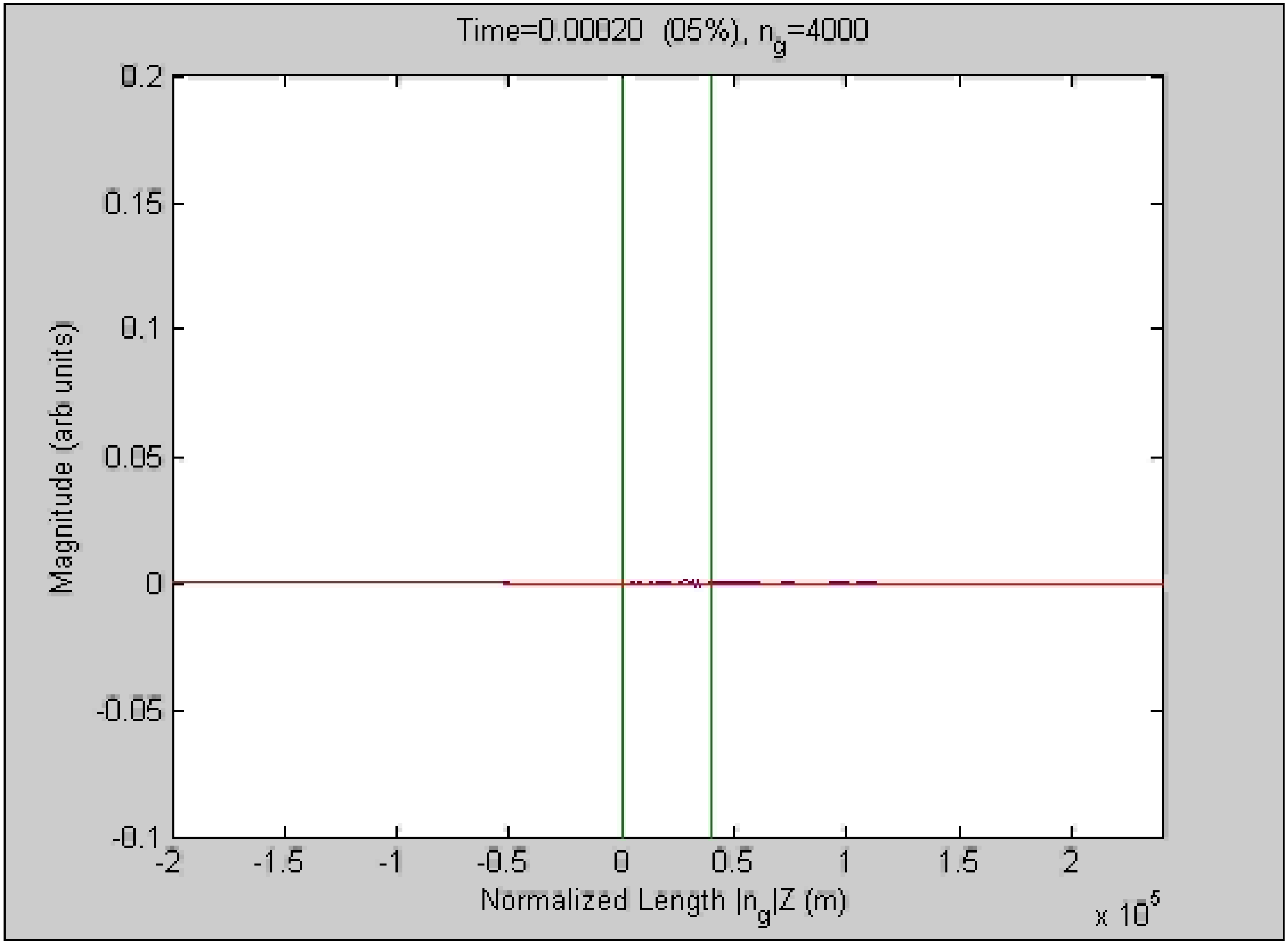
Experimental Results: Backward Propagation in Erbium-Doped Fiber

Normalized: (Amplification removed numerically)

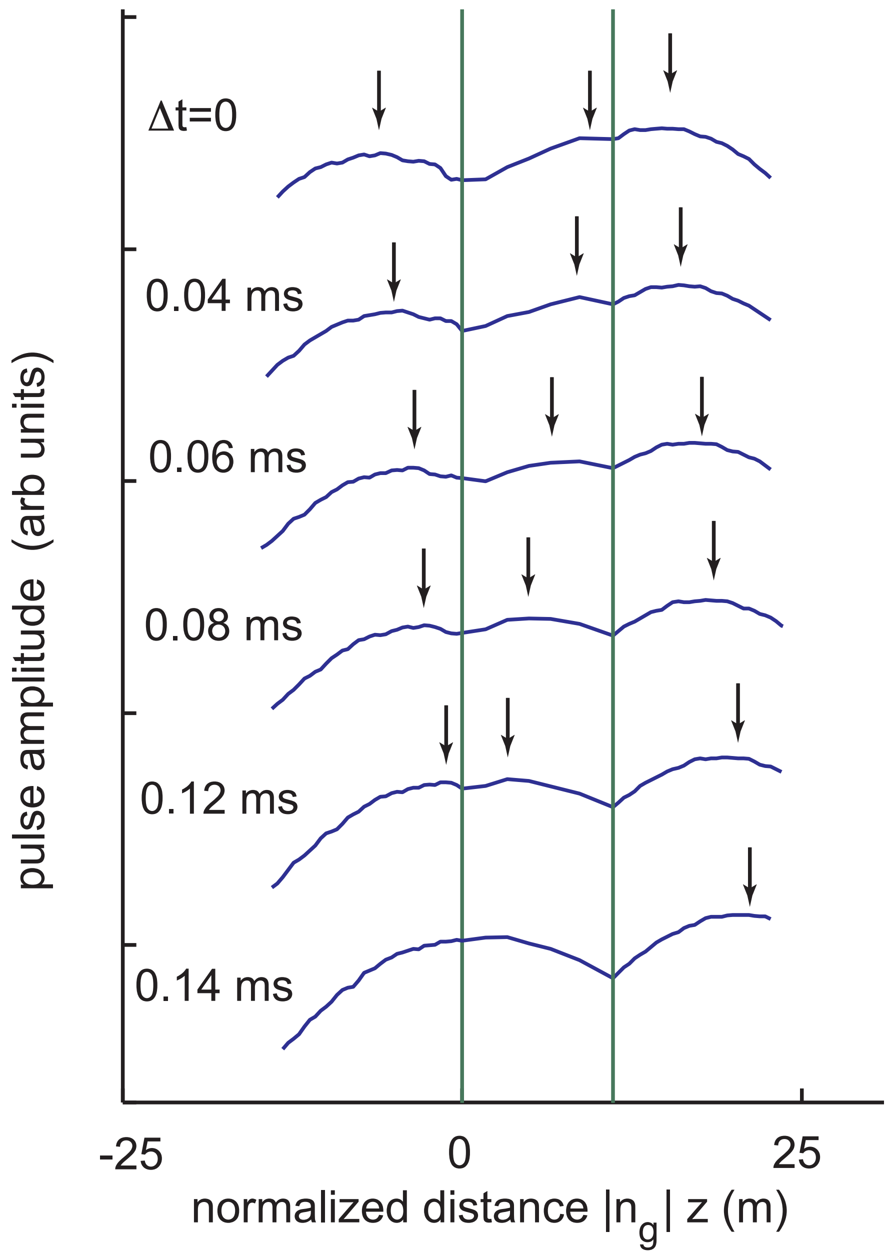


Experimental Results: Backward Propagation in Erbium-Doped Fiber

Un-Normalized



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.

Causality and Superluminality

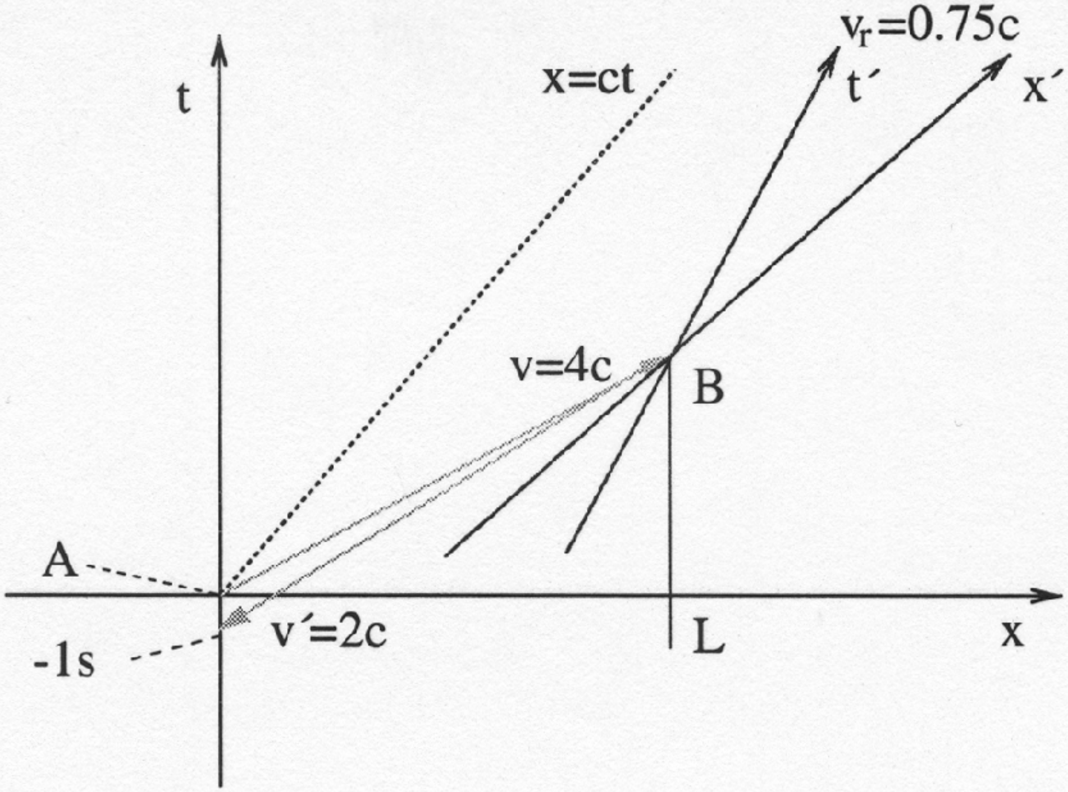
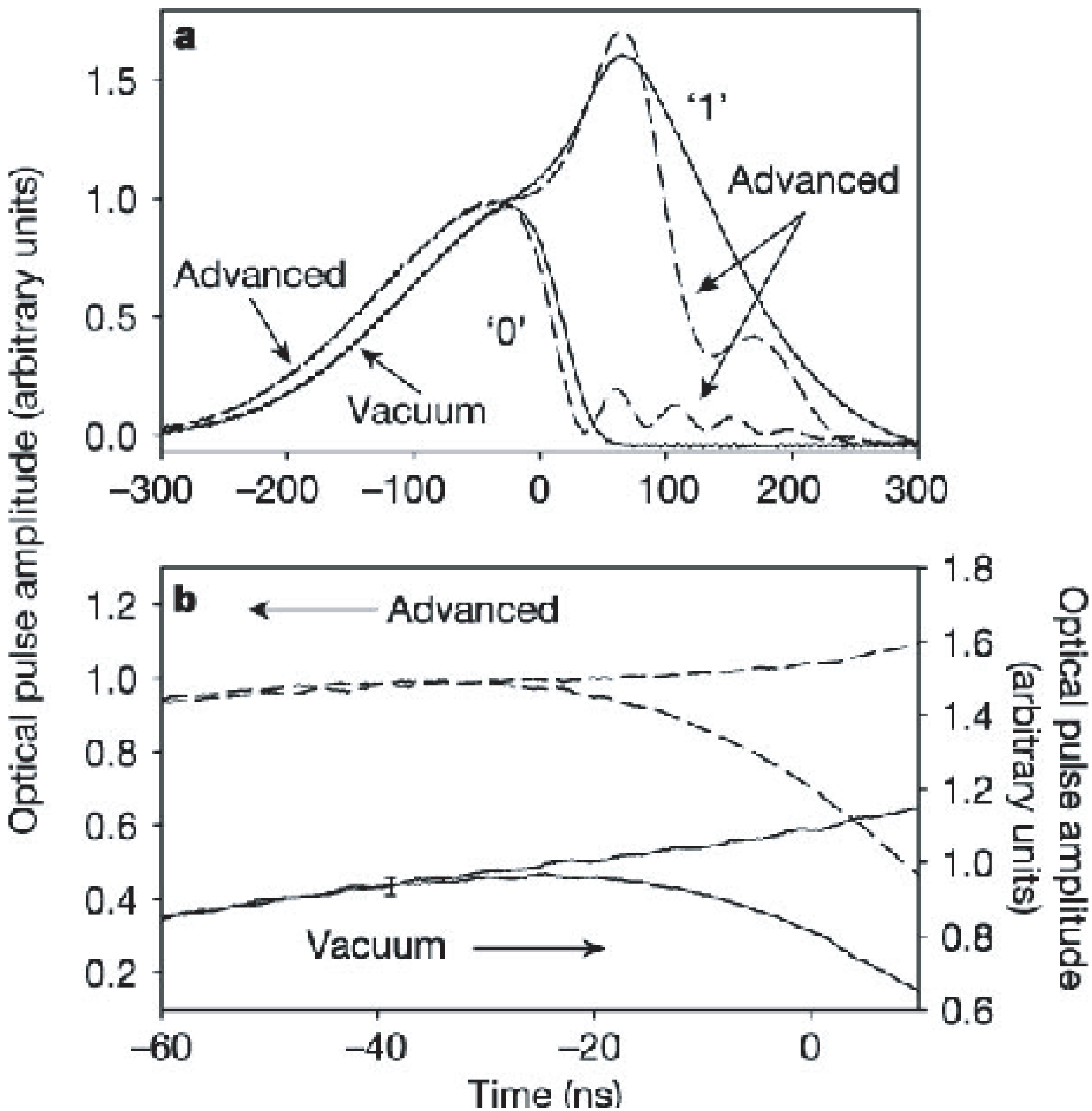


Fig. 6 Coordinates of two inertial observers **A** (0,0) and **B** with $O(x,t)$ and $O'(x',t')$ moving with a relative velocity of $0.75c$. The distance L between **A** and **B** is 2 000 000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v'_s = 2c$. The numbers in the example are chosen arbitrarily. The signal returns -1 s in the past in **A**.

Ann. Phys. (Leipzig) 11, 2002.

Information Velocity in a Fast Light Medium

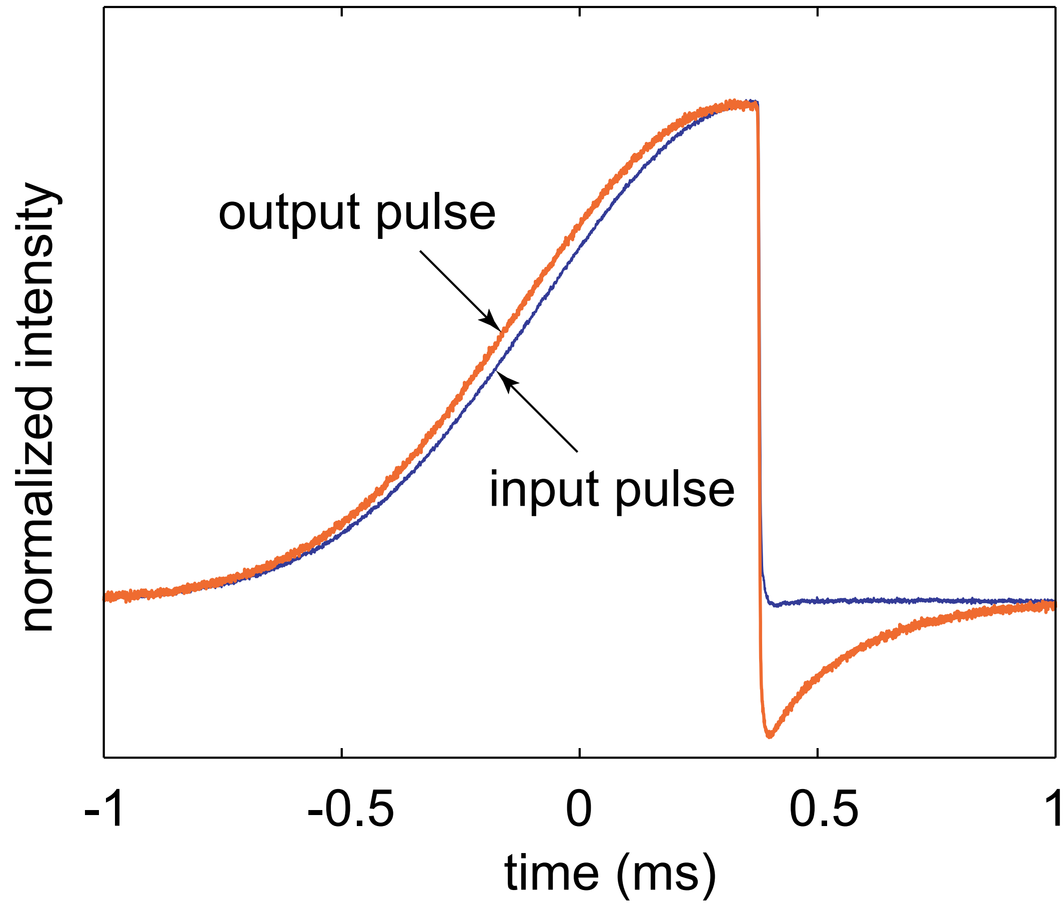


M.D. Stenner, D.J. Gauthier, and M.I. Neifeld, Nature,425 695 (2003).

Pulses are not distinguishable "early."

$v_i \leq c$

Propagation of a Truncated Pulse through Alexandrite as a Fast-Light Medium



Smooth part of pulse propagates at group velocity

Discontinuity propagates at phase velocity

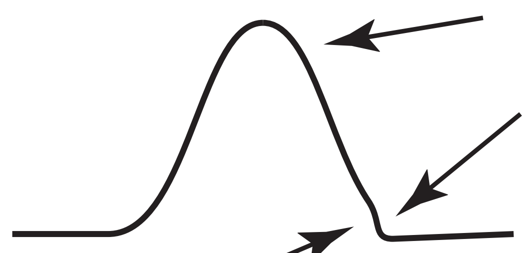
Information Velocity – Tentative Conclusions

In principle, the information velocity is equal to *c* for both slow- and fast-light situations. **So why is slow and fast light even useful?**

Because in many practical situations, we can perform reliable meaurements of the information content only near the peak of the pulse.

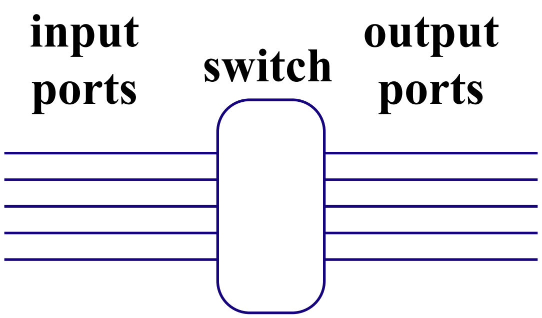
In this sense, useful information often propagates at the group velocity.

In a real communication system it would be really stupid to transmit pulses containing so much energy that one can reliably detect the very early leading edge of the pulse.

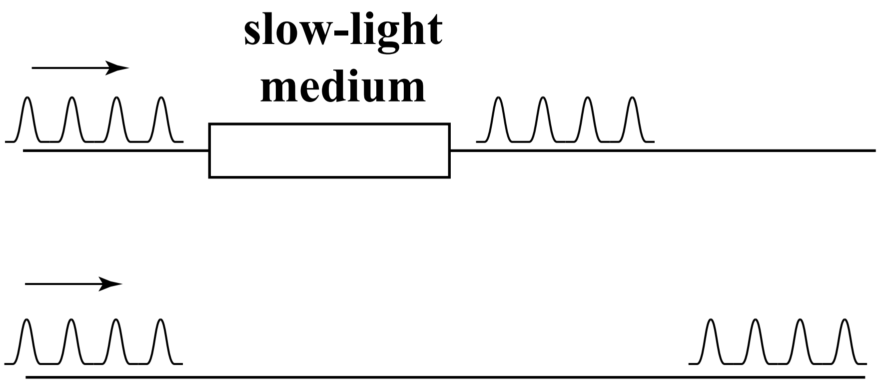


Slow Light and Optical Buffers

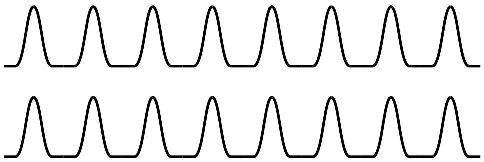
All-Optical Switch



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.

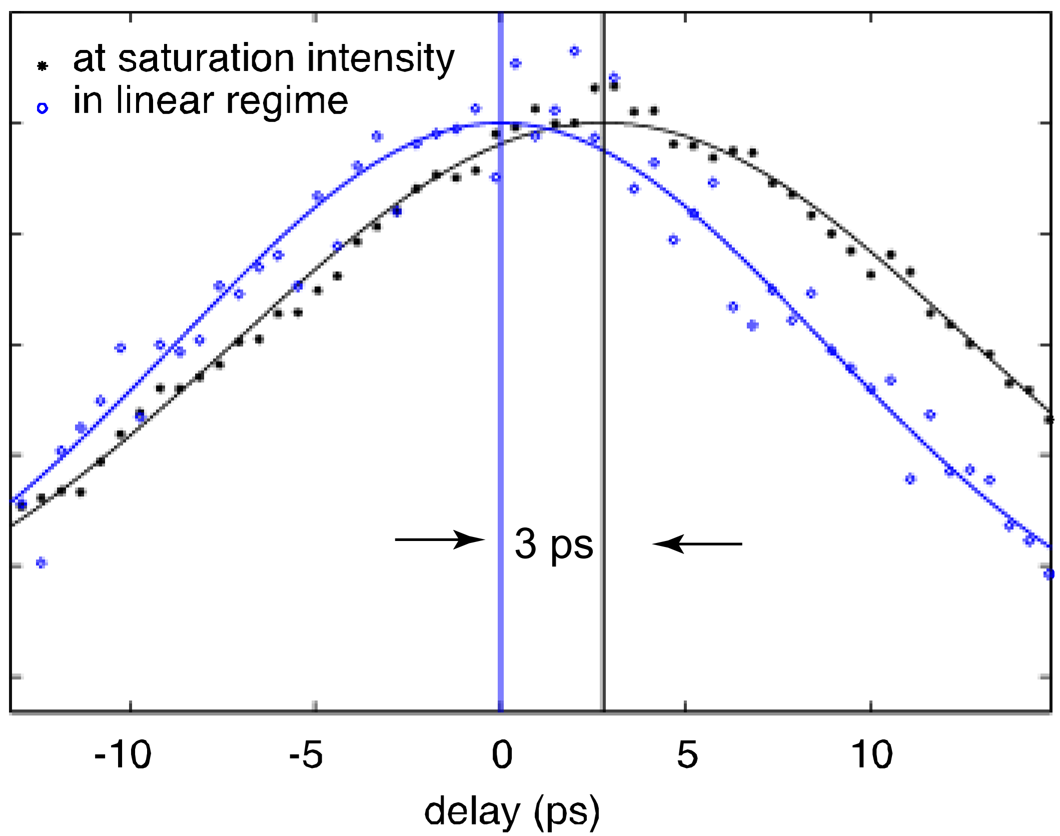
Daniel Blumenthal, UC Santa Barbara; Alexander Gaeta, Cornell University; Daniel Gauthier, Duke University; Alan Willner, University of Southern California; Robert Boyd, John Howell, University of Rochester

Slow Light in SC Quantum Dot Structures

PbS Quantum Dots (2.9 nm diameter) in liquid solution

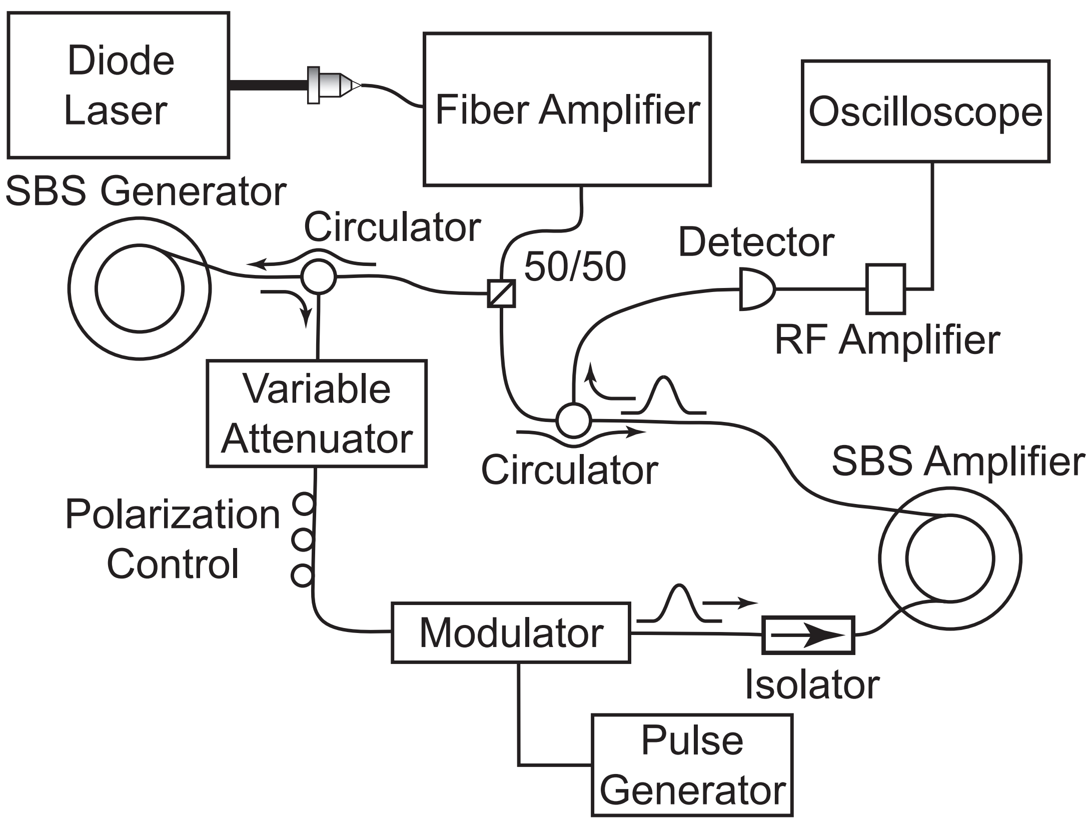
Excite with 16 ps pulses at 795 nm; observe 3 ps delay

30 ps response time (literature value)

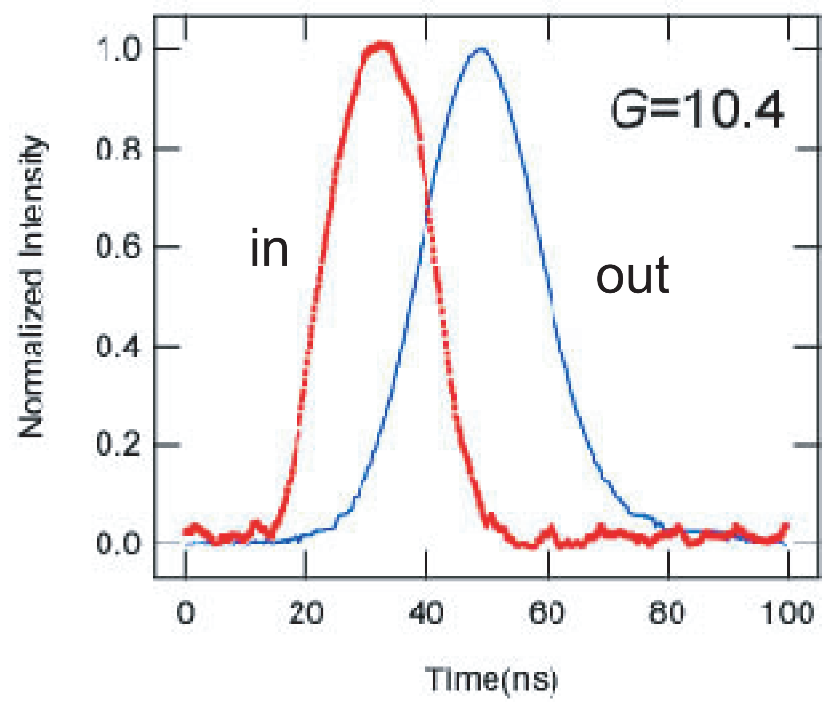


Slow-Light via Stimulated Brillouin Scattering

- 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).

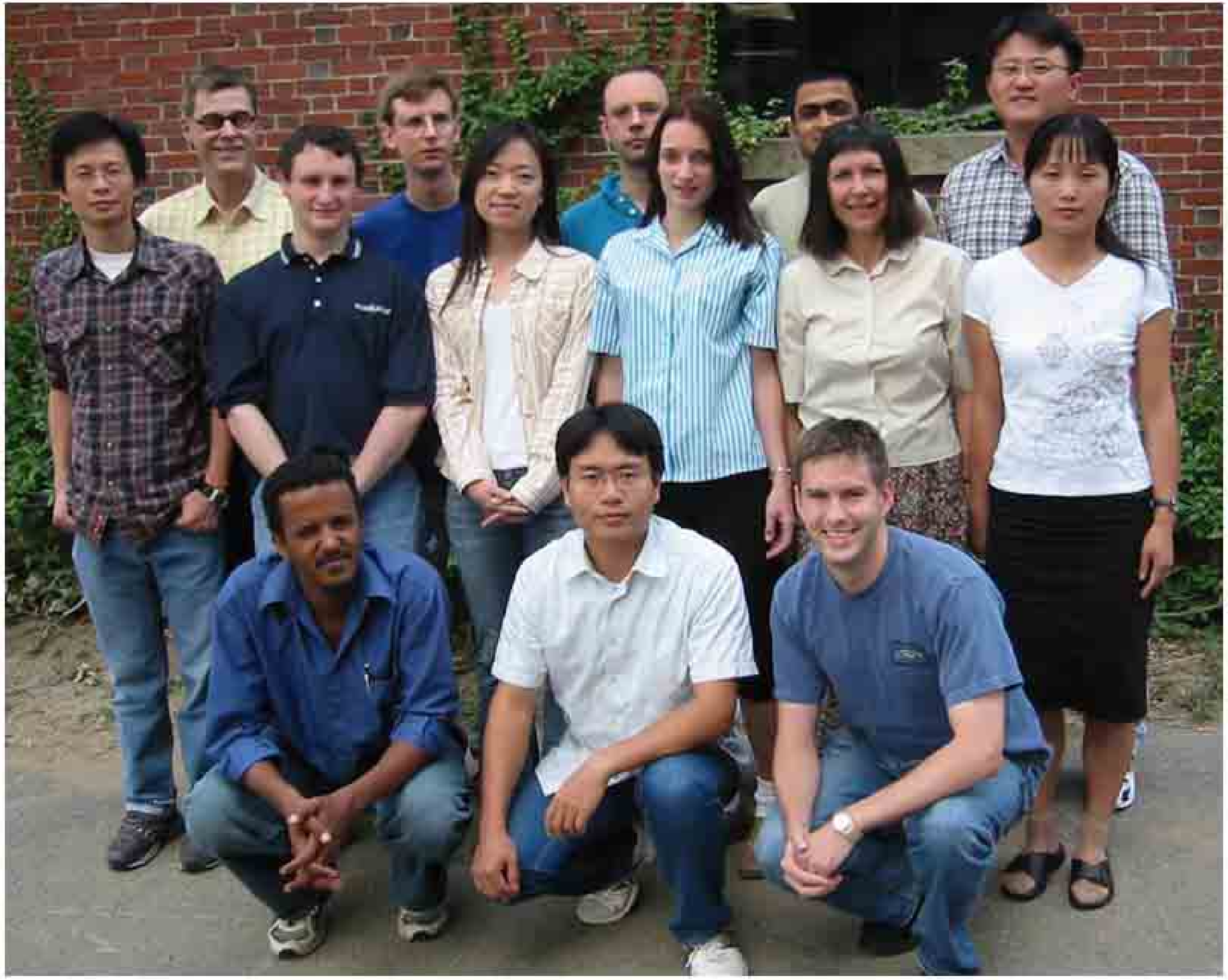
Summary

Slow-light techniques hold great promise for applications in telecom and quantum information processing

Good progress being made in devloping new slow-light techniques and applications

Different methods under development possess complementary regimes of usefullness

Special Thanks to My Students and Research Associates



Thank you for your attention!

Our results are posted on the web at:

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