Slowing Down the Speed of Light

Applications of "Slow" and "Fast" Light

Robert W. Boyd

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with Mathew Bigelow, Nick Lepeshkin, Aaron Schweinsberg, Petros Zerom, and others.

Presented at RPI, April 12, 2005.

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)?

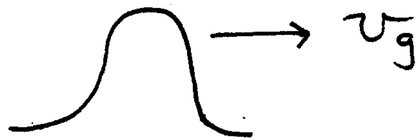
Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.

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 $\quad v_g = \dfrac{d\omega}{dk}$

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

Thus

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

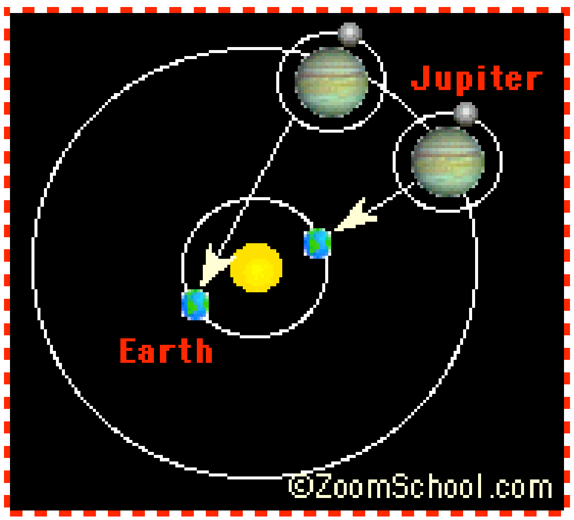
Thus $\quad n_g \neq n \quad$ in a dispersive medium!

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

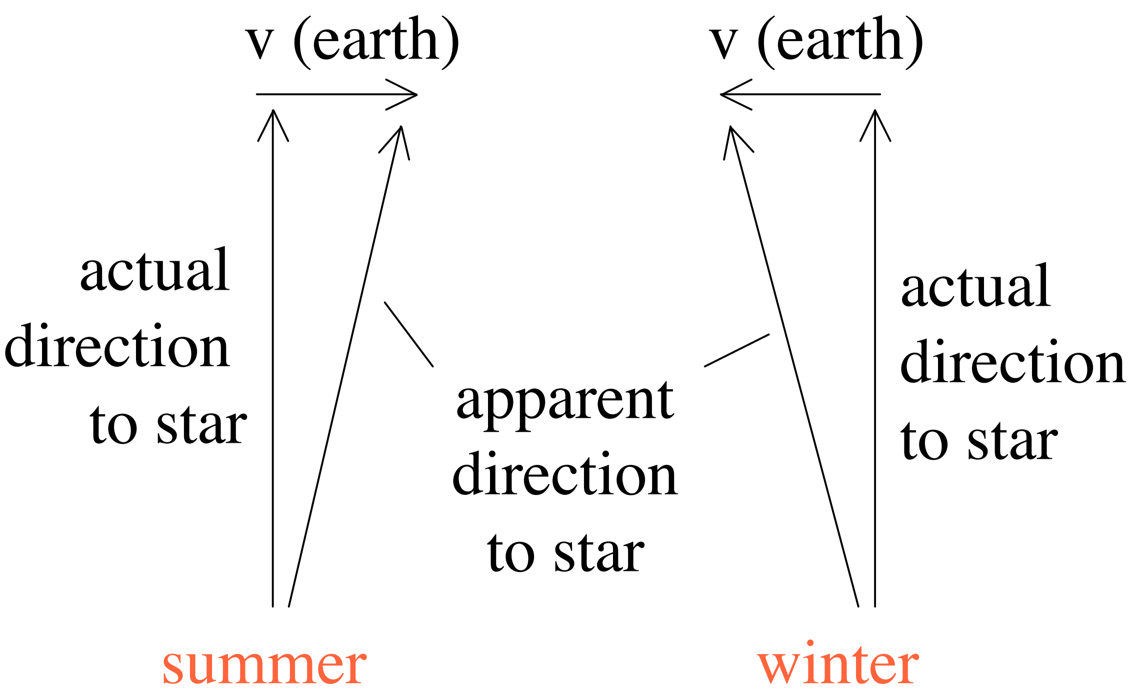
(Actually, light transit time from sun to earth is just over 8 minutes, and c = 299,793 km/sec)

*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.



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

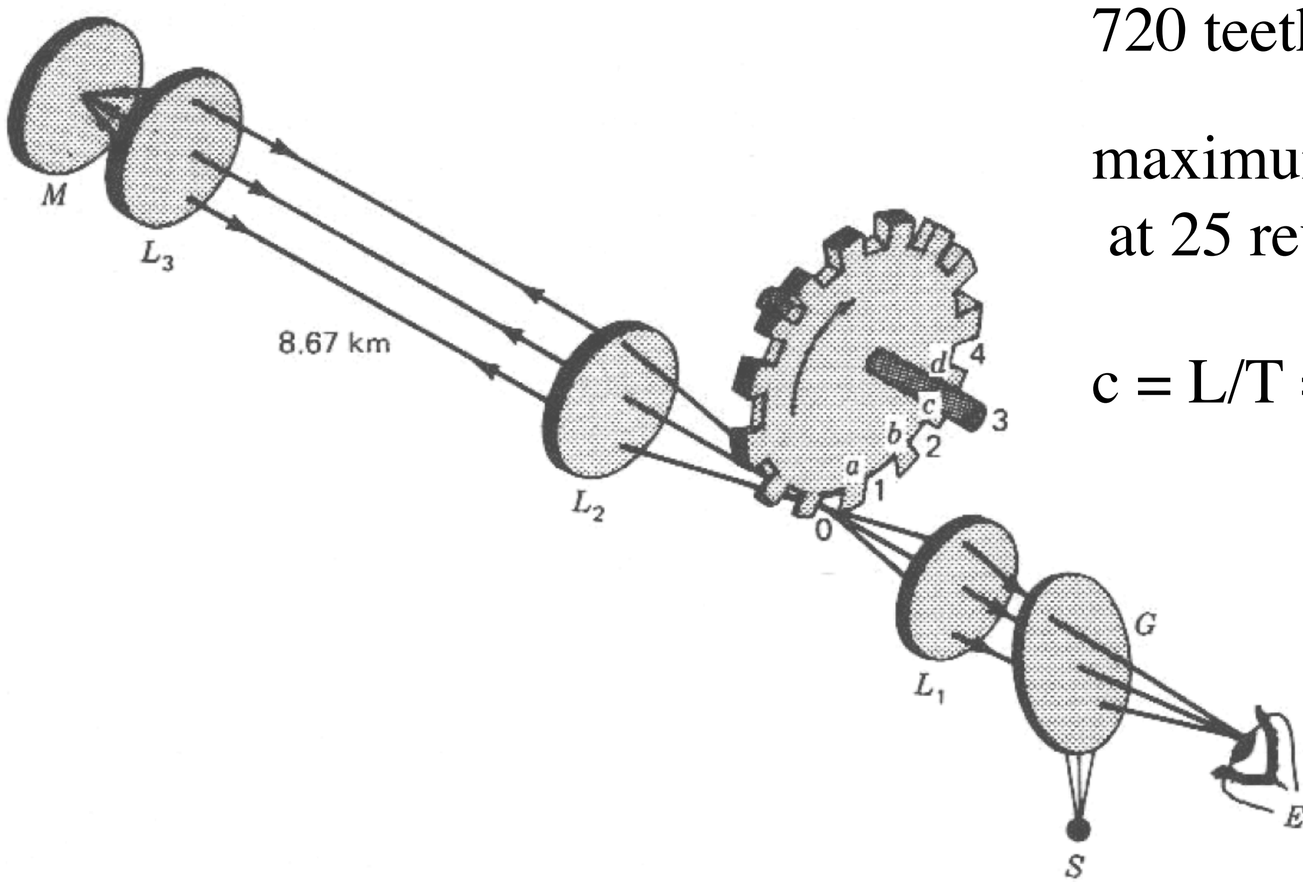
$$\tan\alpha = \frac{v(\text{earth})}{c}$$

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

Determination of the Velocity of Light

Laboratory Methods

Fizeau (1849) Time-of-flight method



720 teeth in wheel

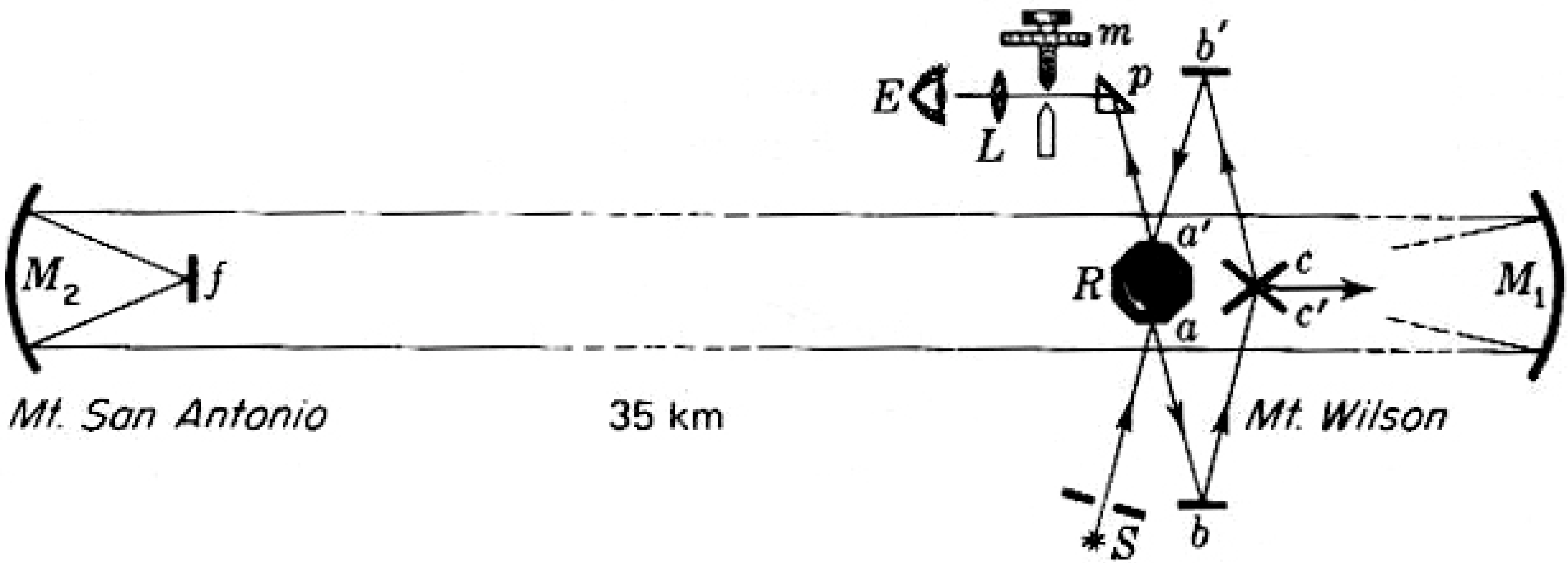
maximum transmission
at 25 revolutions/sec

c = L/T = 320,000 km/s

Determination of the Velocity of Light

Laboratory Methods

Michelson (1926); Improved time of flight method.



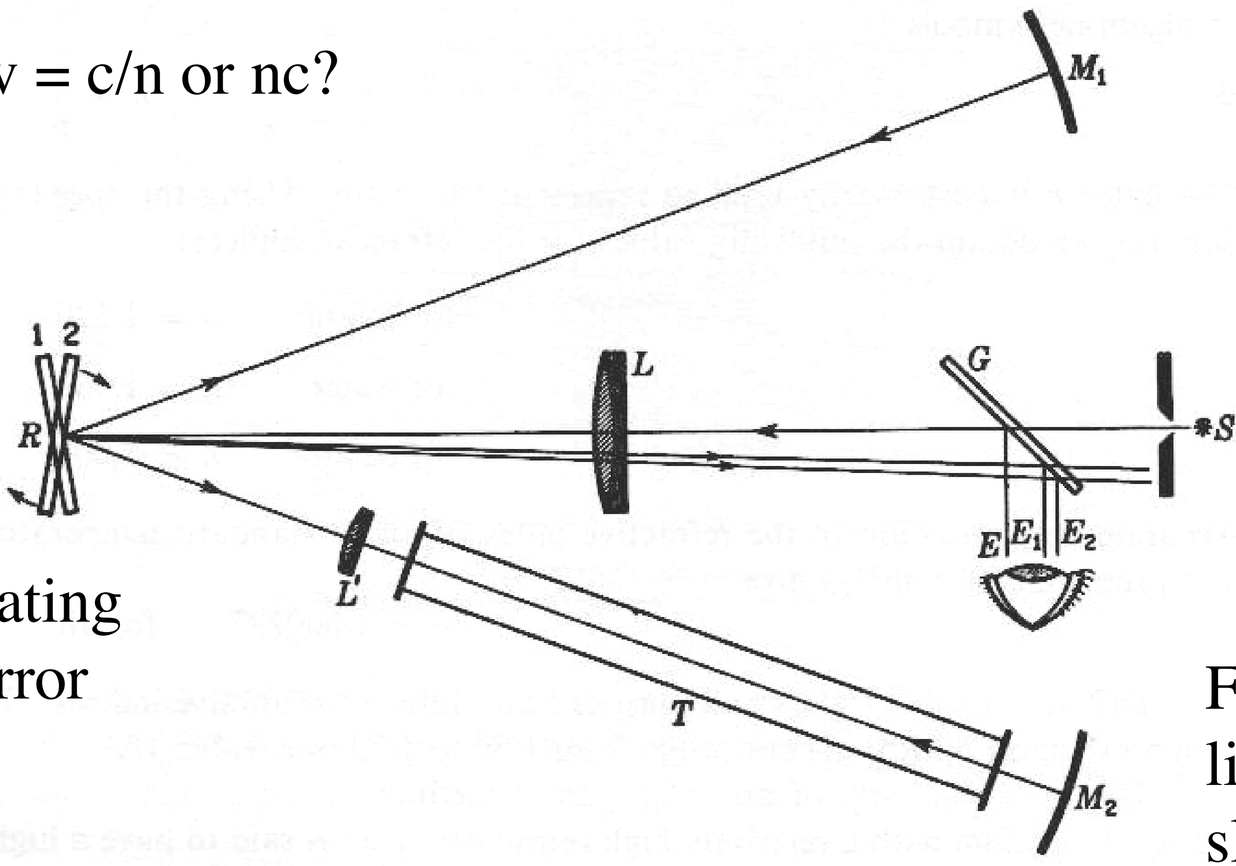
Rotating octagonal mirror

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?



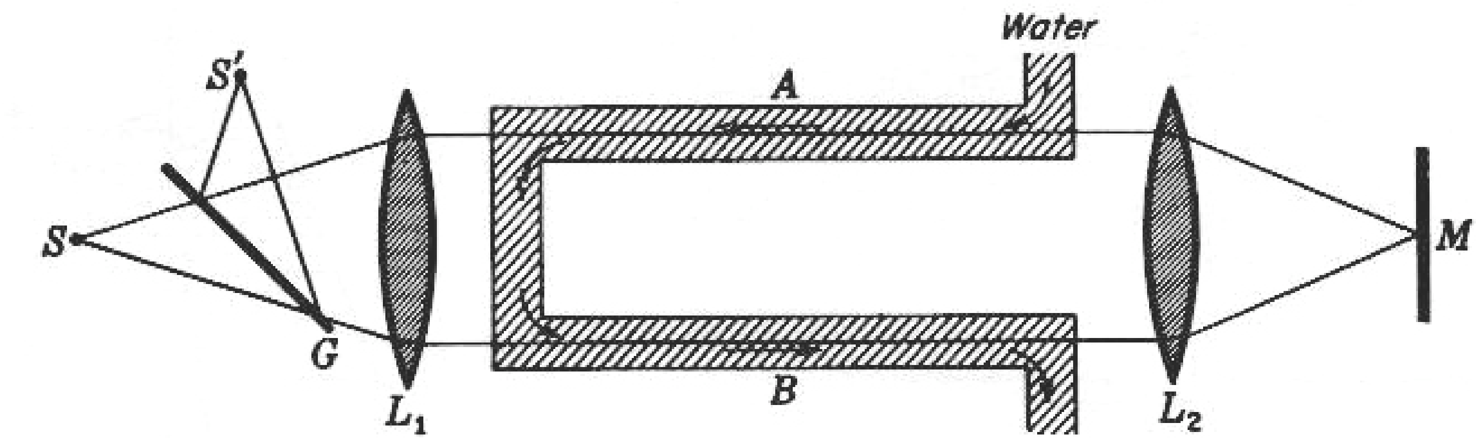
rotating mirror

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

Scientific Genealogy

Robert Boyd was a student of Charles Townes at the University of California, Berkeley.

Charles Townes was a students of William Smythe at the California Institute of Technology.

William Smythe was a student of Henry Gale at the University of Chicago.

Henry Gale was a student of Albert Michelson at the University of Chicago.

Albert Michelson was largely self-taught, although he worked with both Simon Newcomb and Hermann von Helmholtz.

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

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

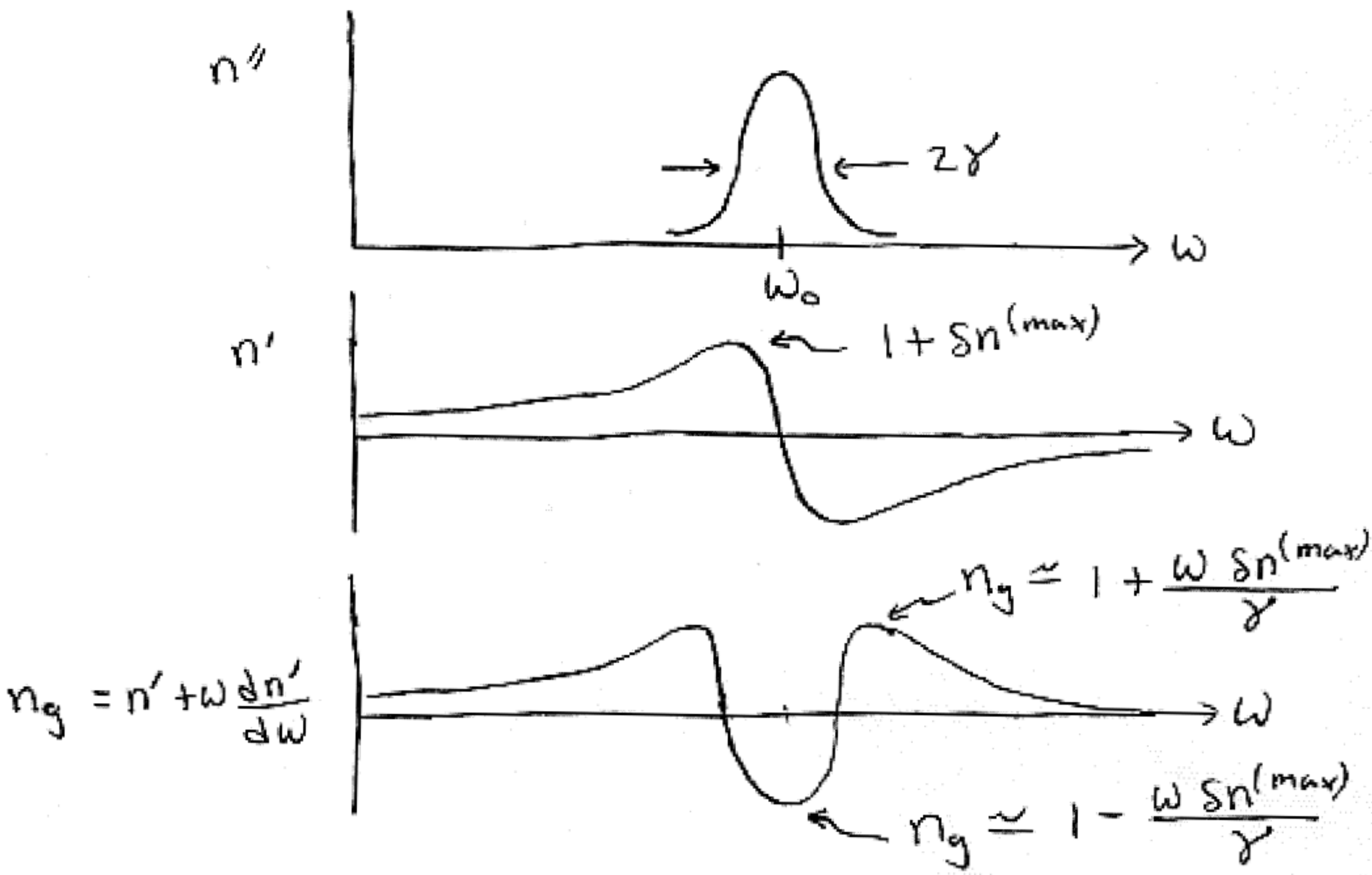
Light Propagation in Atomic Vapors

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

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

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

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



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

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

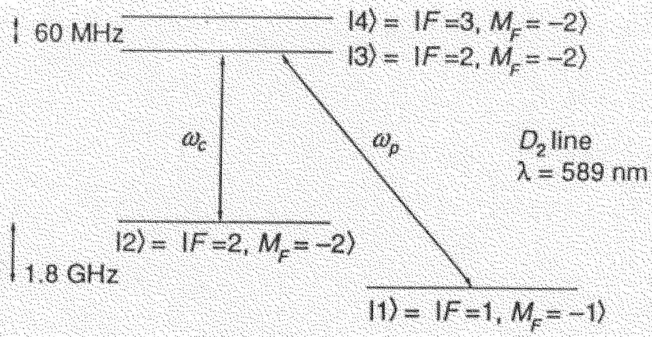
and others

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

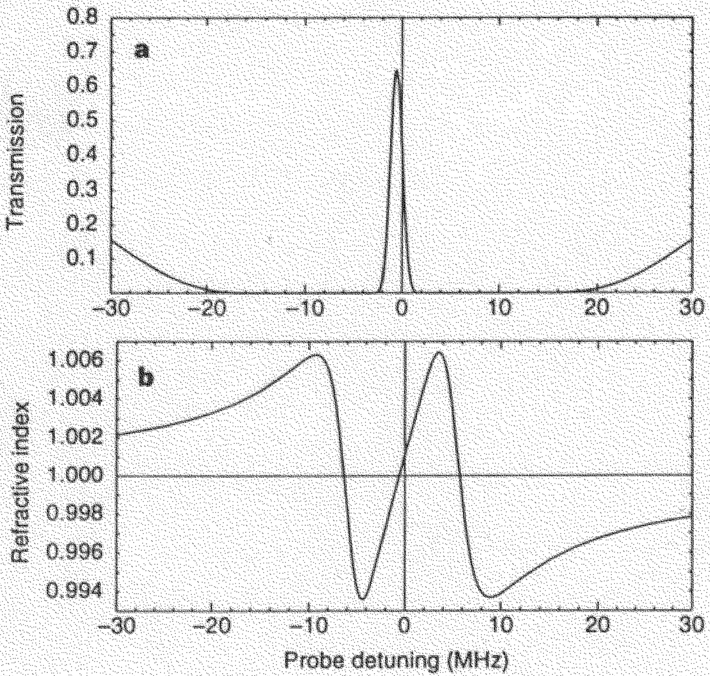
Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§

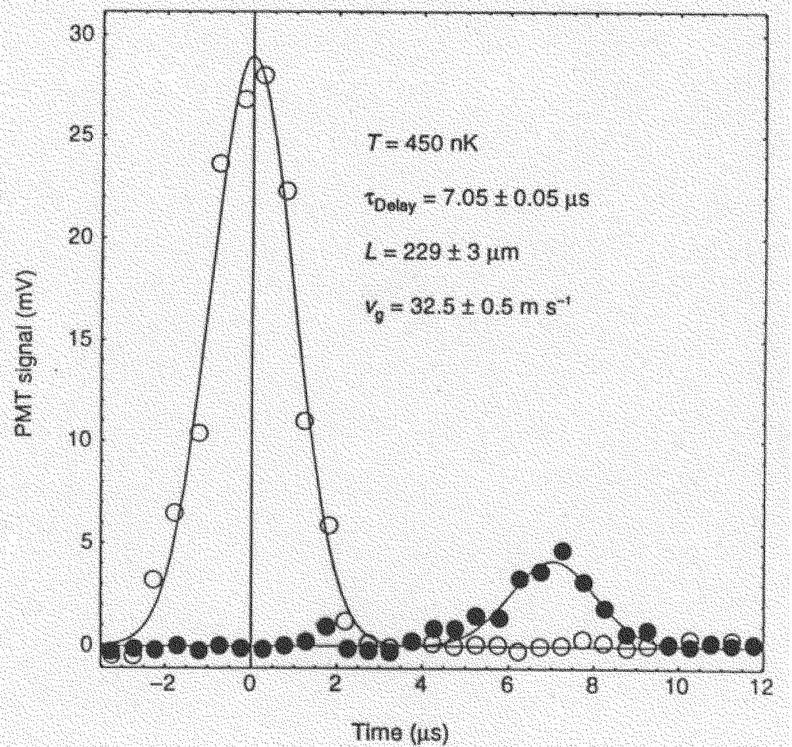
* *Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142, USA*
† *Department of Physics,* § *Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*
‡ *Edward L. Ginzton Laboratory, Stanford University, Stanford, California 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

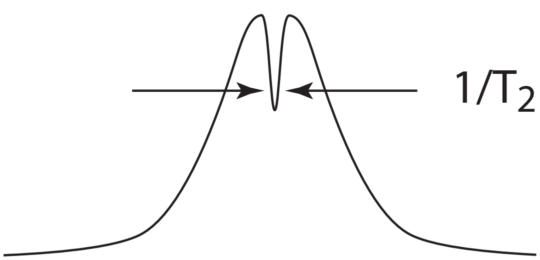
Need a large dn/dω. (How?)

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

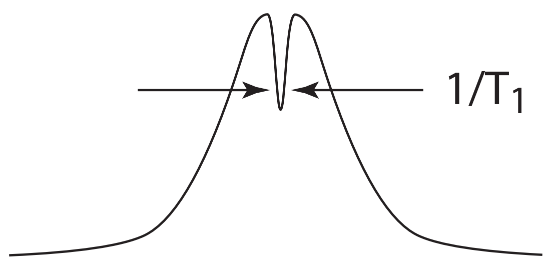
Well-known (to the few people how know it well) how to do so:

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

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



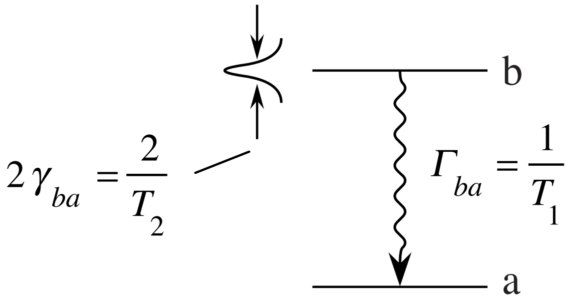
inhomogeneously broadened medium

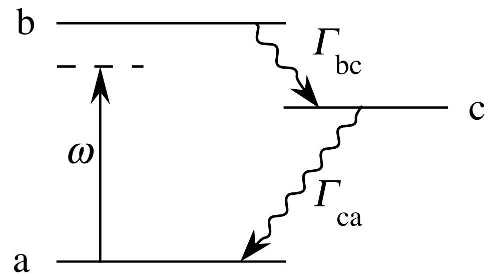


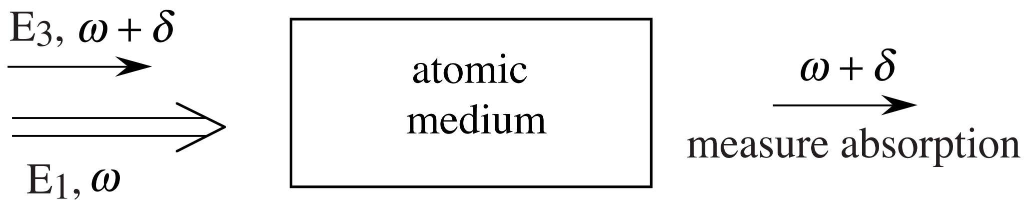
homogeneously broadened medium (or inhomogeneously broadened)

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:

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

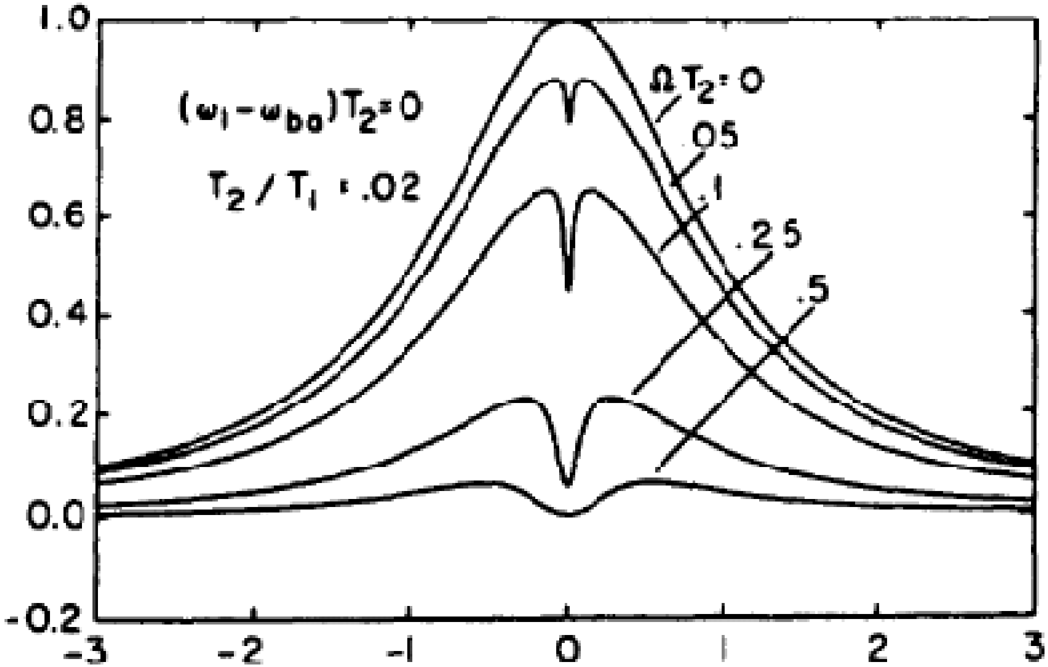
Probe-beam absorption:

$$\alpha(\omega + \delta) = \alpha_0 \left[w^{(0)} - \frac{\Omega^2 T_2}{T_1} \frac{1}{\delta^2 + \beta^2} \right]$$

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 ($T_2 << T_1$)

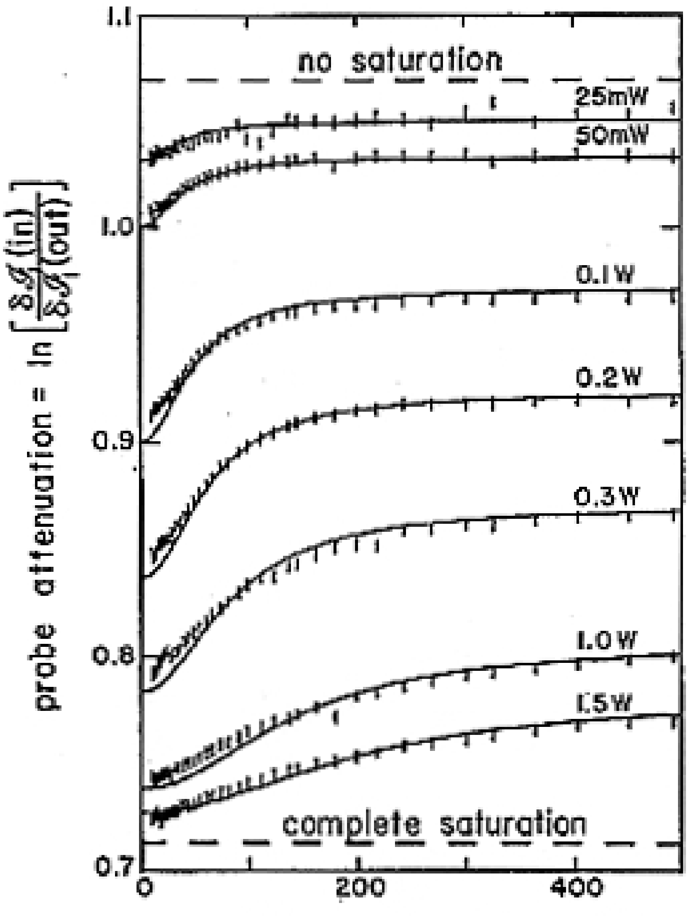


pump-probe detuning (units of $1/T_2$)

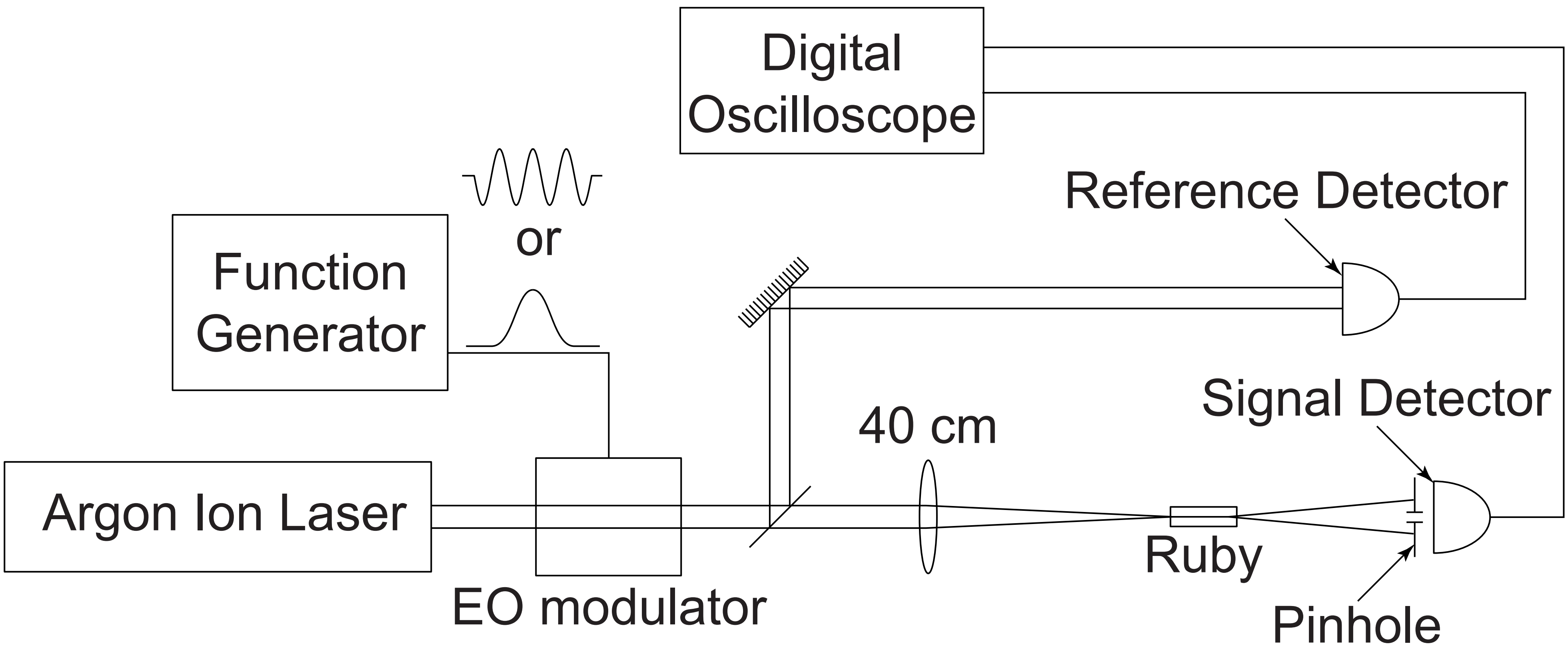
Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

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

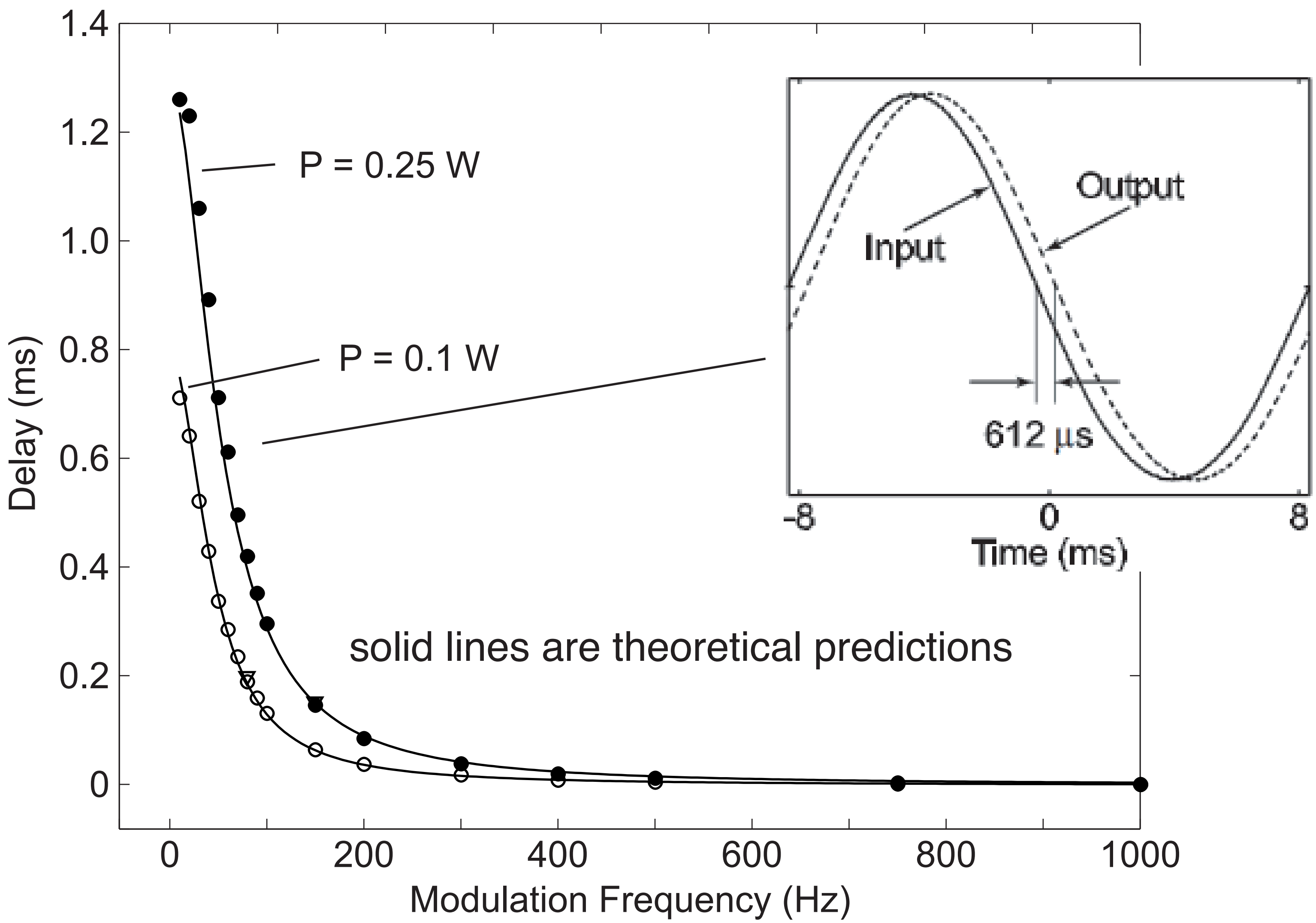


Slow Light Experimental Setup



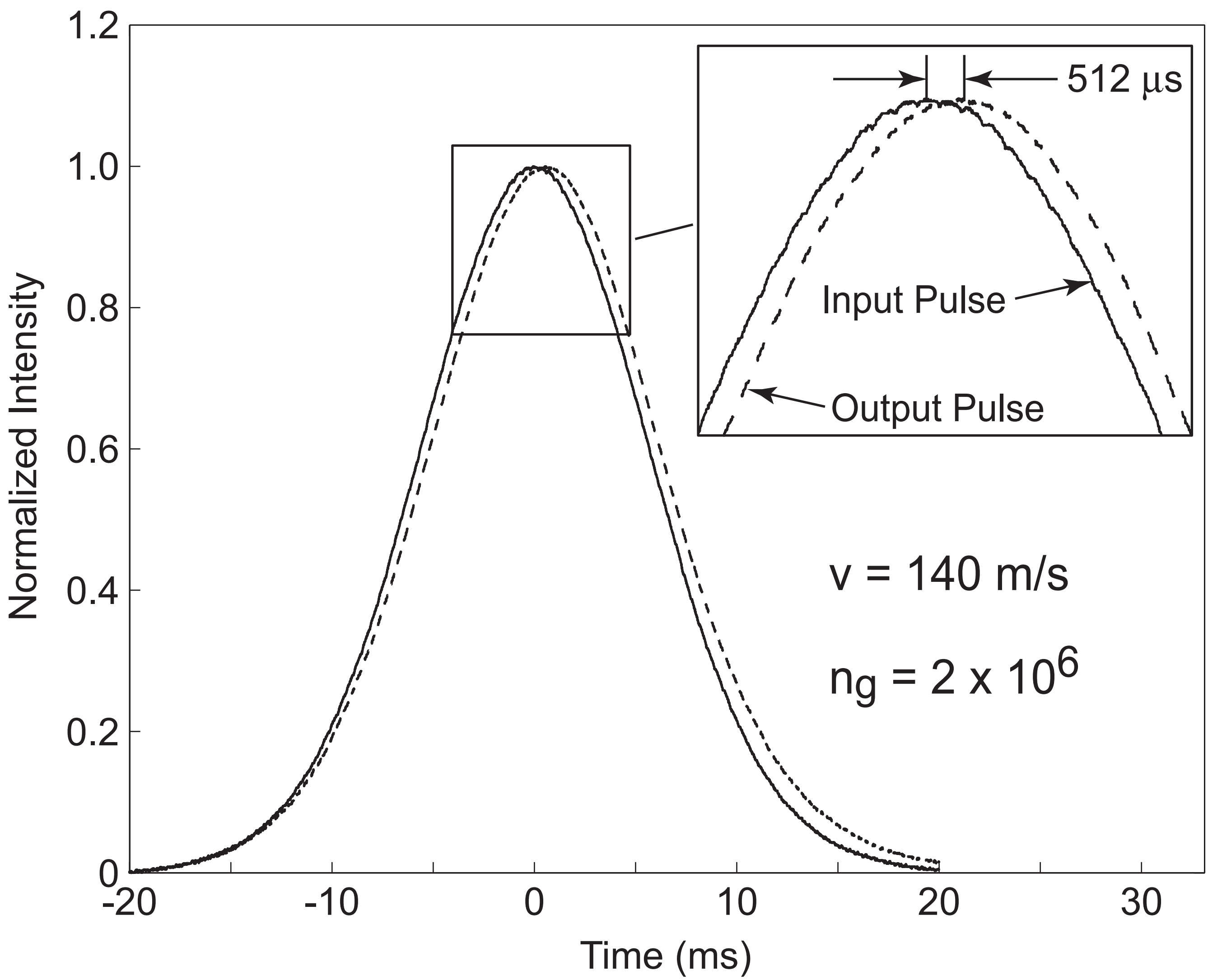
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



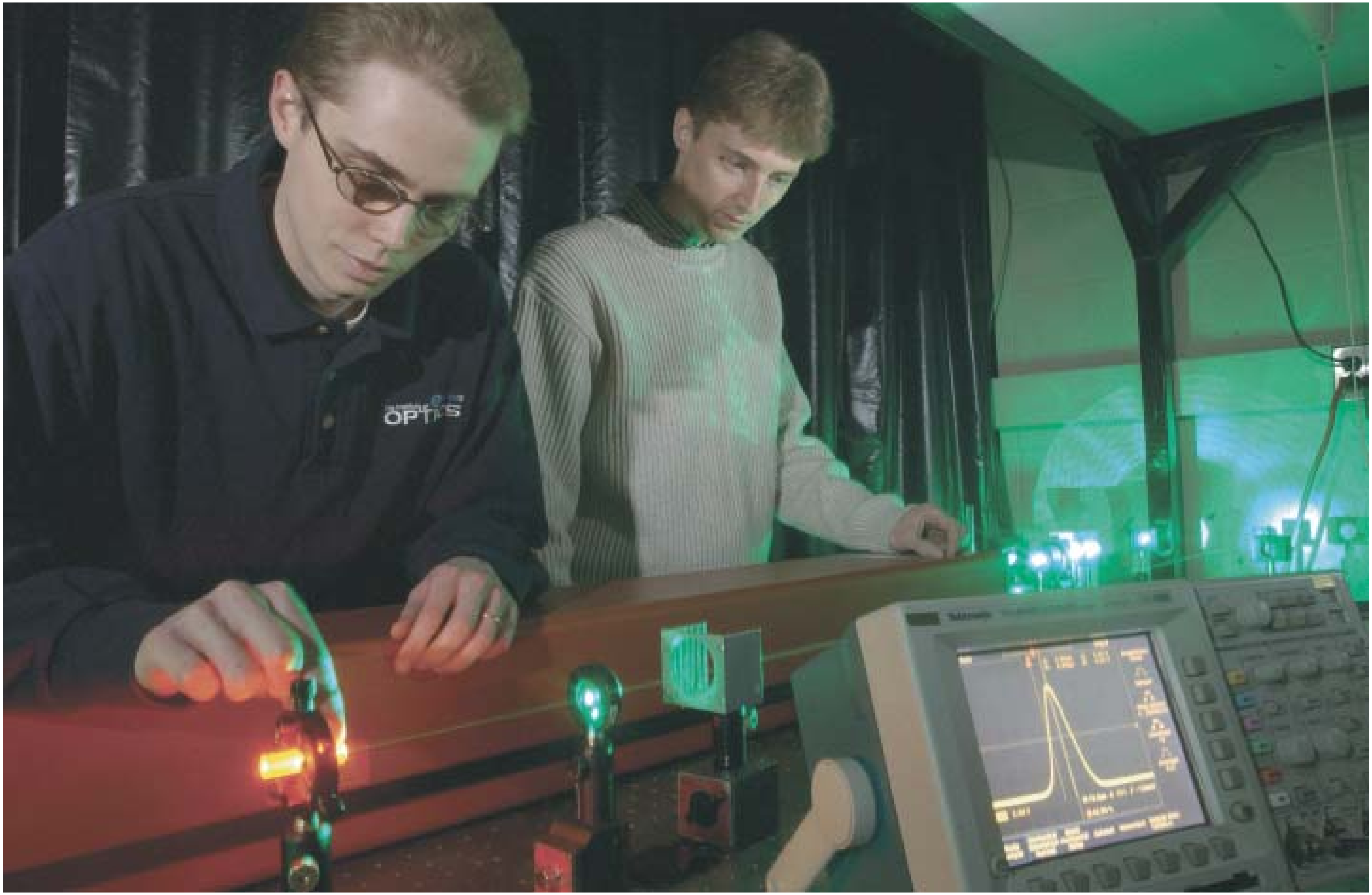
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

Gaussian Pulse Propagation Through Ruby

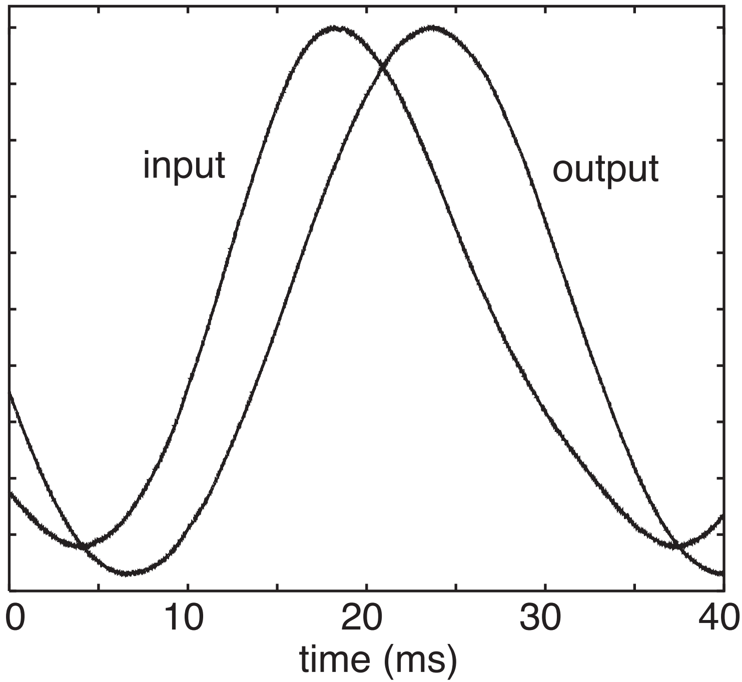


No pulse distortion!

Matt Bigelow and Nick Lepeshkin in the Lab



Slow Light in Ruby -- Greater Pulse Separation



60 degree delay = 1/6 of a period

Advantages of Coherent Population Oscillations for Slow Light

Works in solids

Works at room temperature

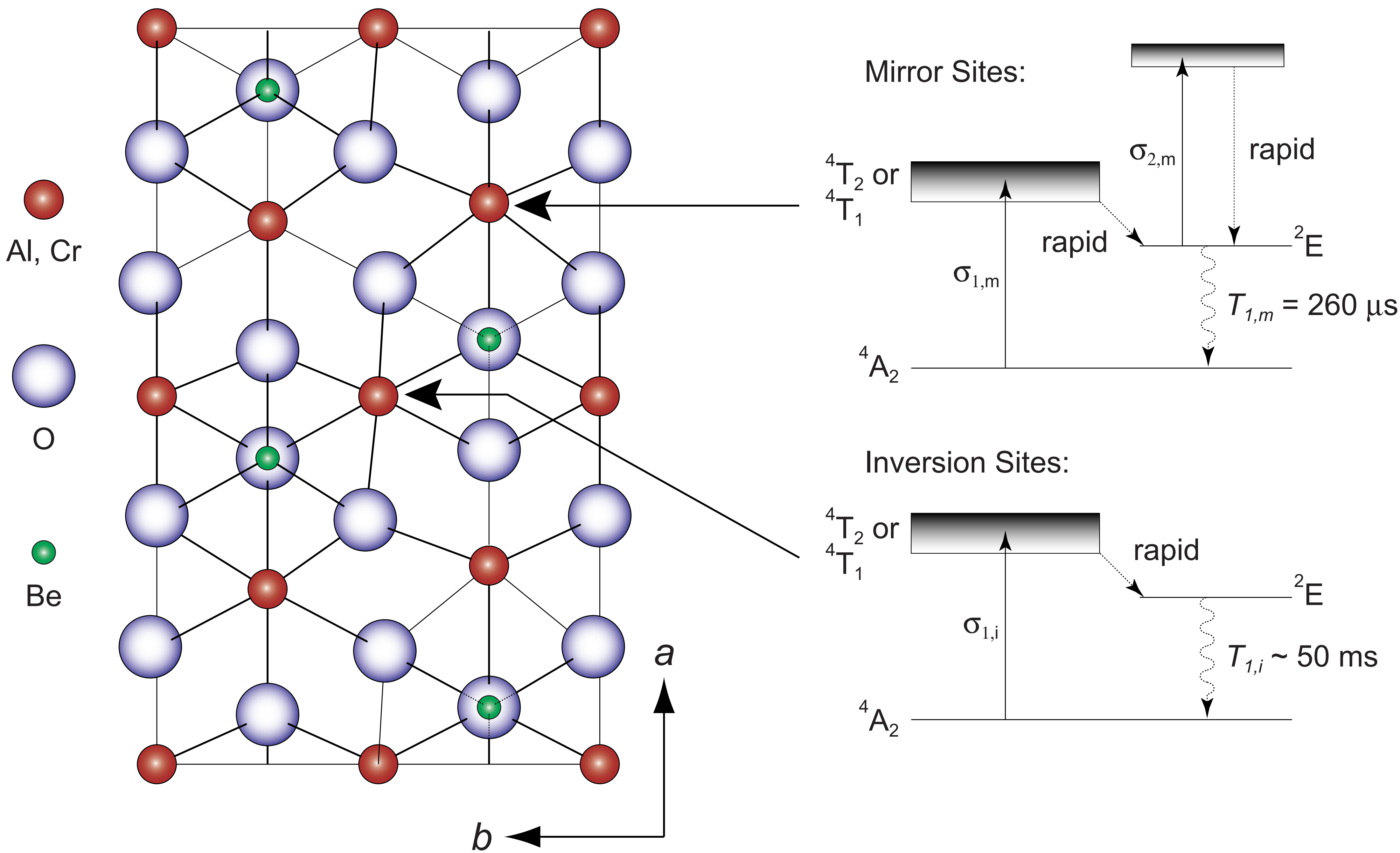
Insensitive of dephasing processes

Laser need not be frequency stabilized

Works with single beam (self-delayed)

Delay can be controlled through input intensity

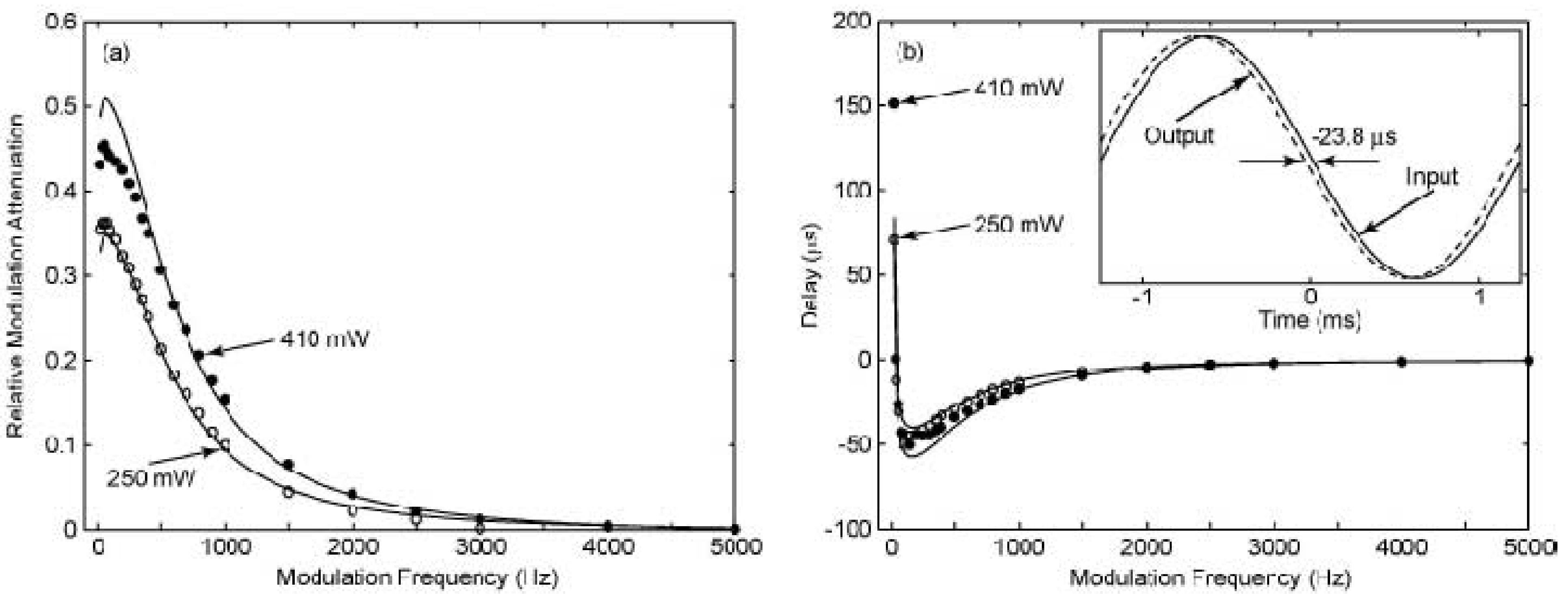
Alexandrite Displays both Saturable and Inverse-Saturable Absorption



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

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.

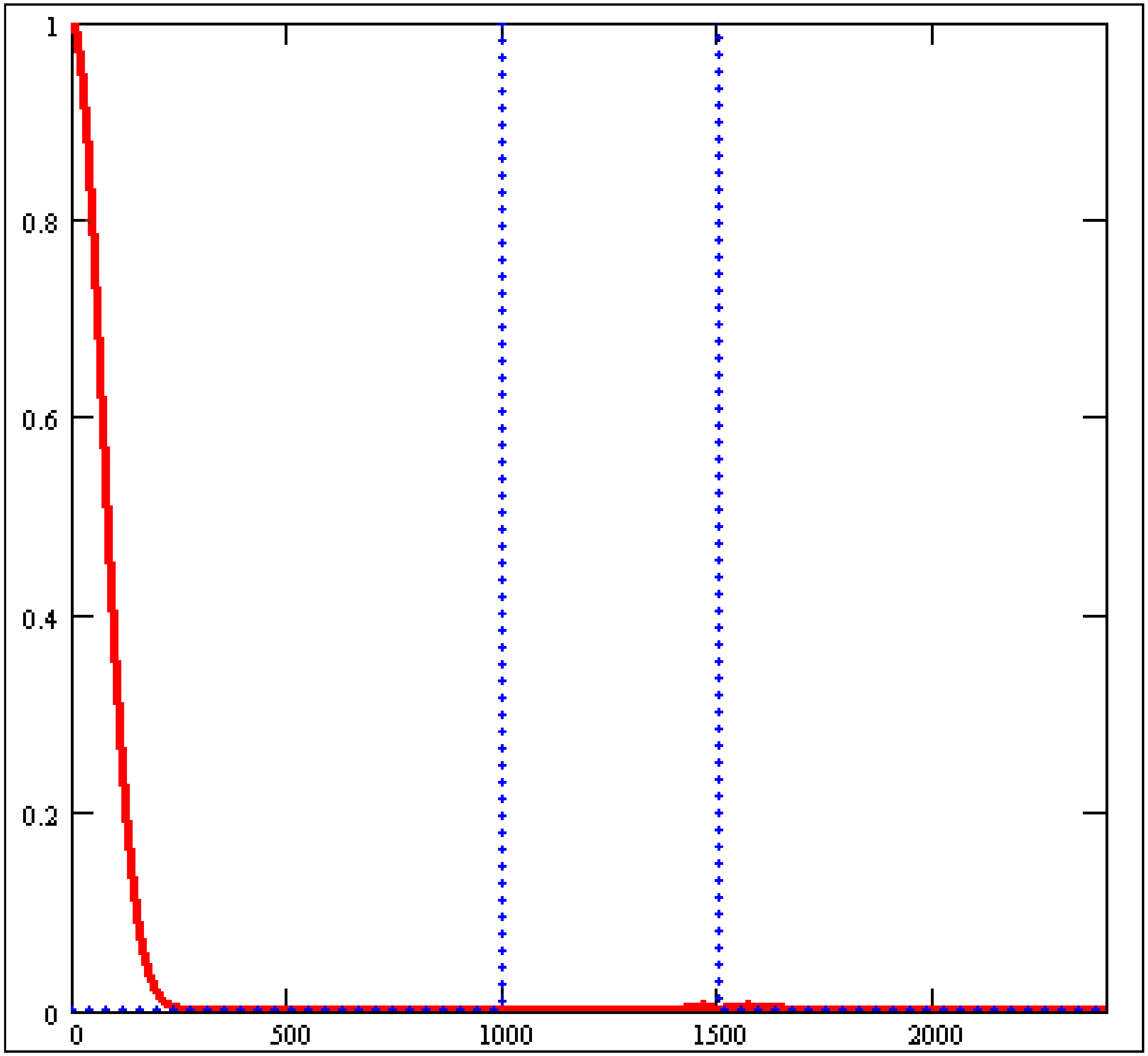
Assume an input pulse with a Gaussian temporal profile.

Study three cases:

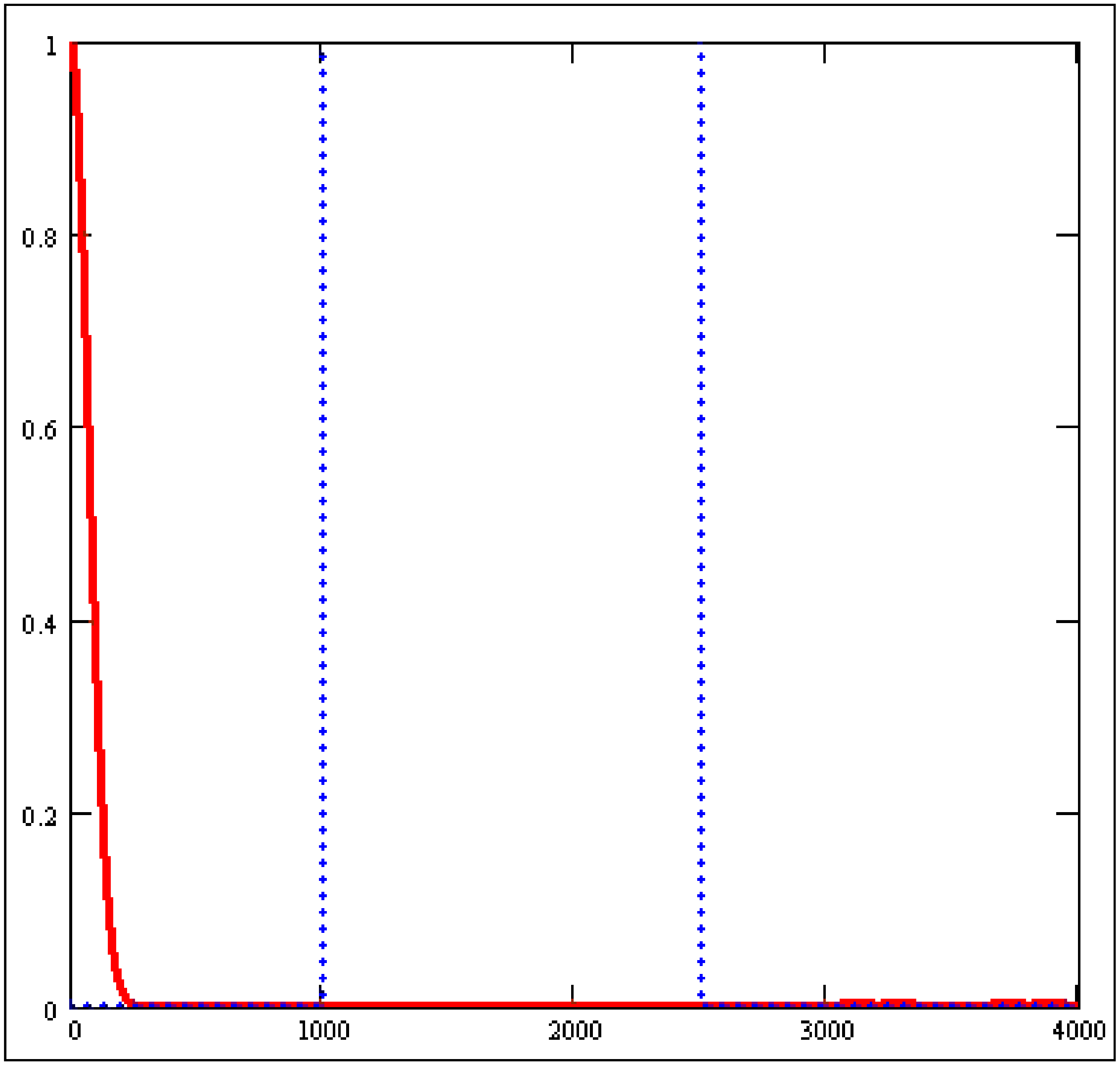
Slow light $v_g = 0.5\ c$

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

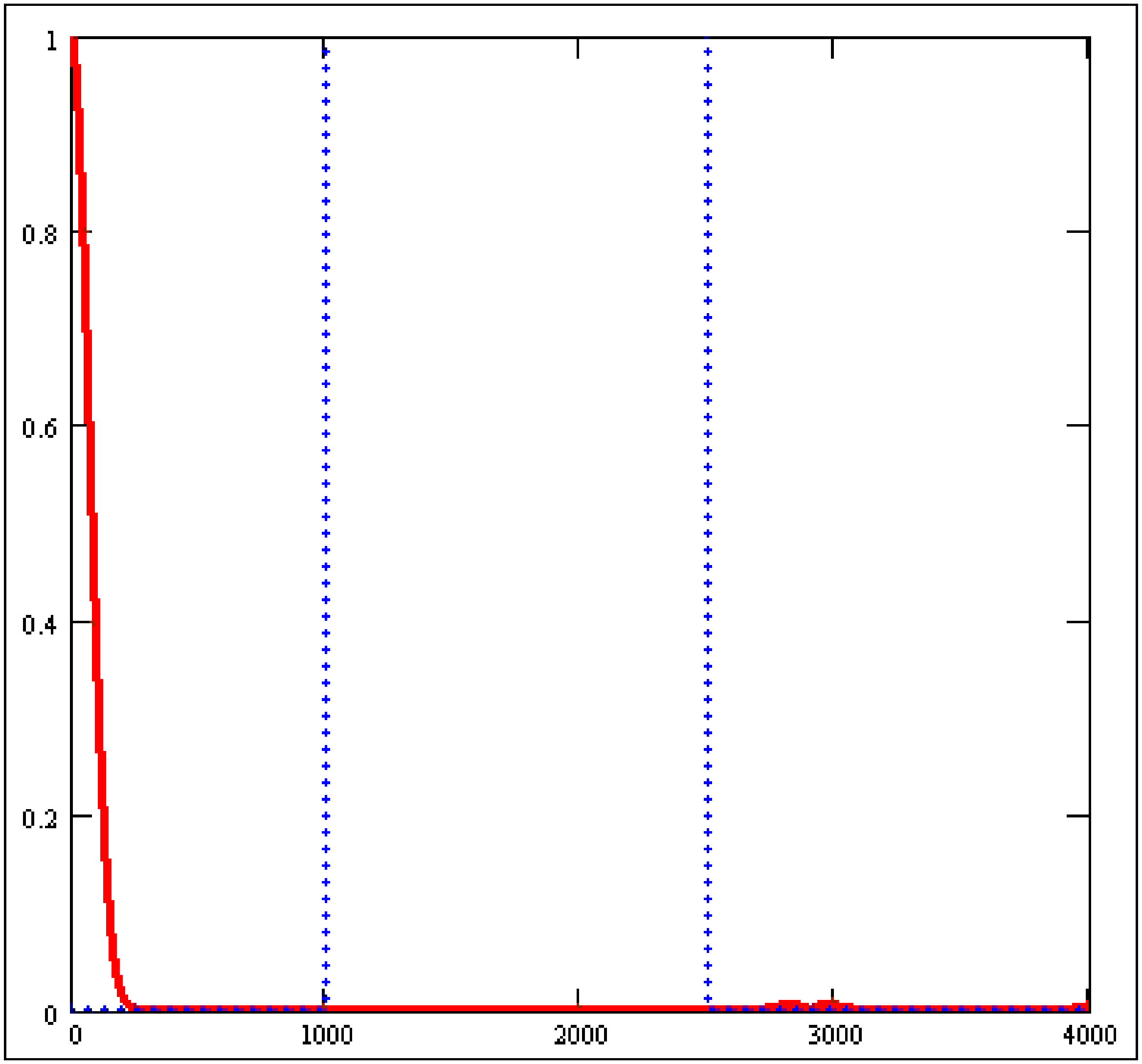
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



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)



Causality and Superluminality

G. Nimtz and A. Haibel, Basics of Superluminal Signals 169

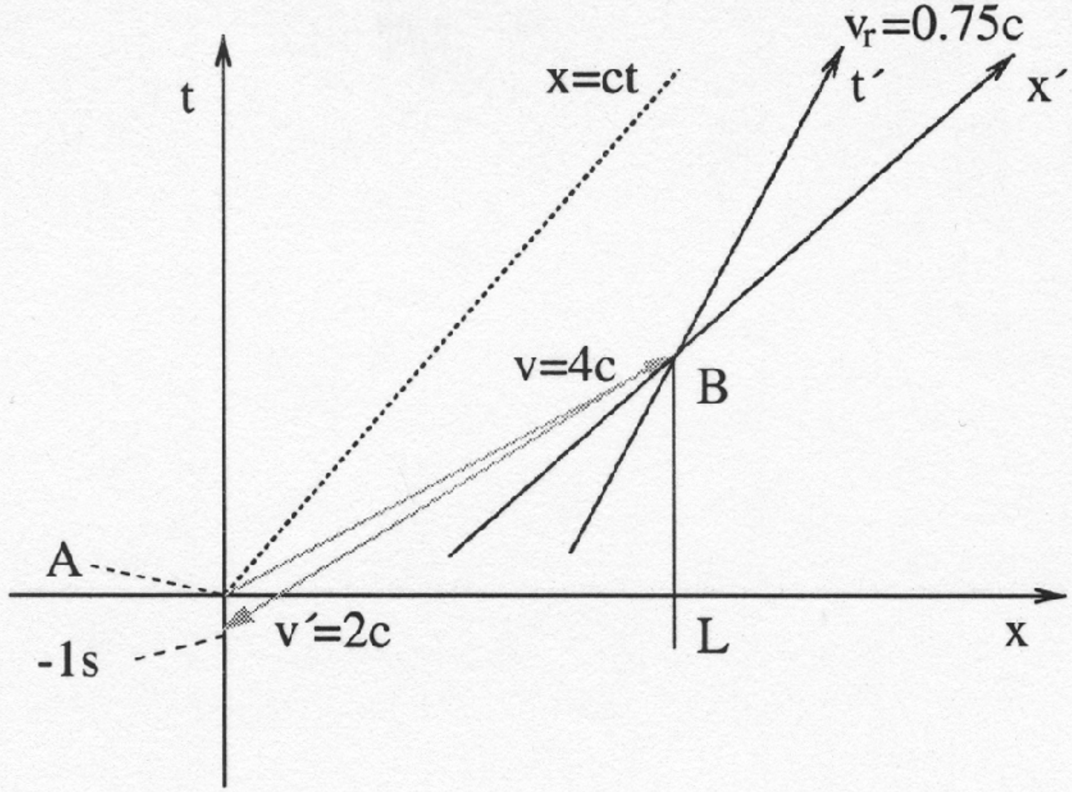
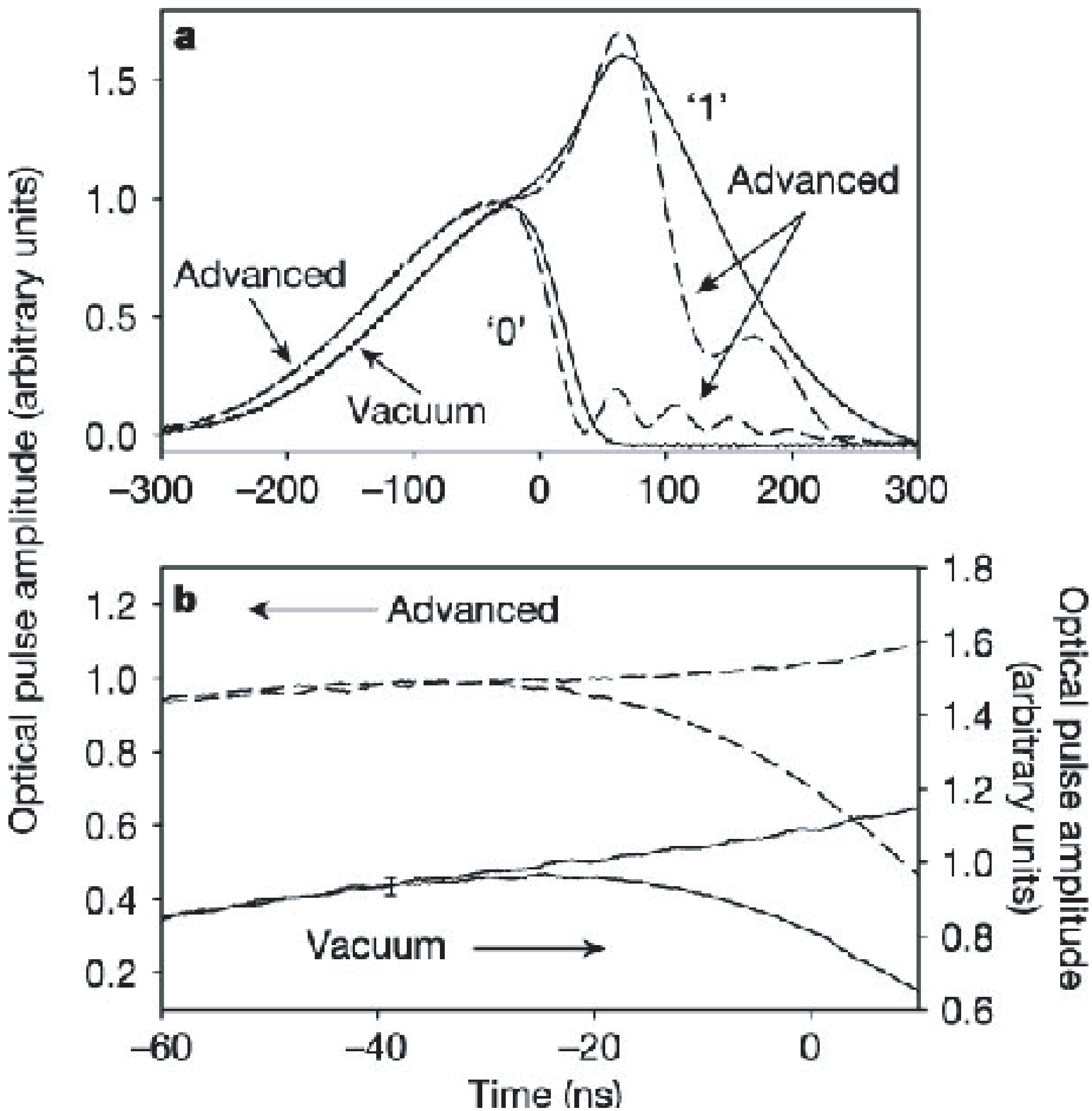


Fig. 6 Coordinates of two inertial observers **A** (0,0) and **B** with $O(x,t)$ and $O'(x',t')$ moving with a relative velocity of $0.75c$. The distance L between **A** and **B** is 2 000 000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v'_s = 2c$. The numbers in the example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

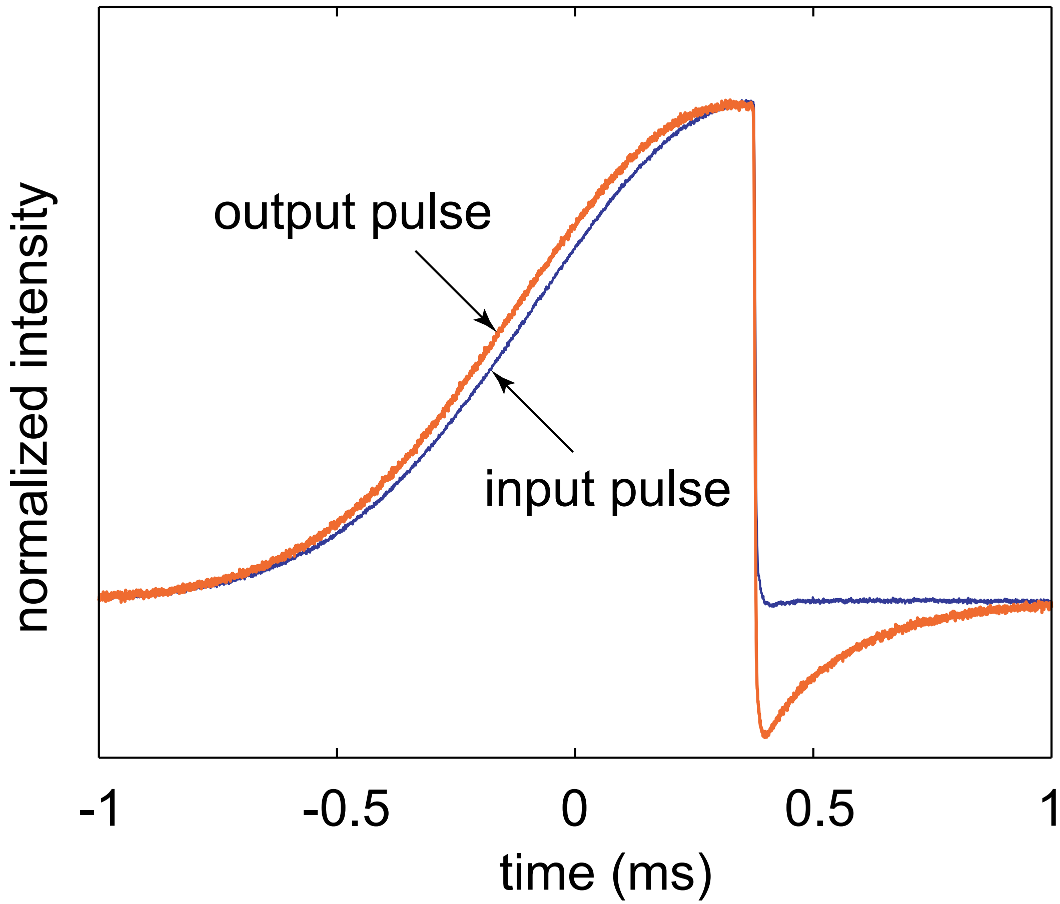


M.D. Stenner, D.J. Gauthier, and M.I. Neifeld, Nature,425 695 (2003).

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

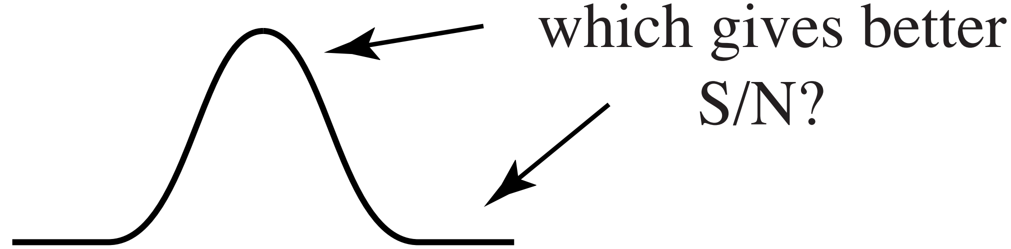
Discontinuity propagates at phase velocity

Information Velocity – Tentative Conclusions

In principle, the information velocity is equal to *c* for both slow- and fast-light situations. (*Analog information velocity*)

But in almost all practical situations, the information velocity is essentially equal to the group velocity. (*Digital information velocity*)

This is my personal opinion. The reason I think this is that 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 and Fast Light --What Next?

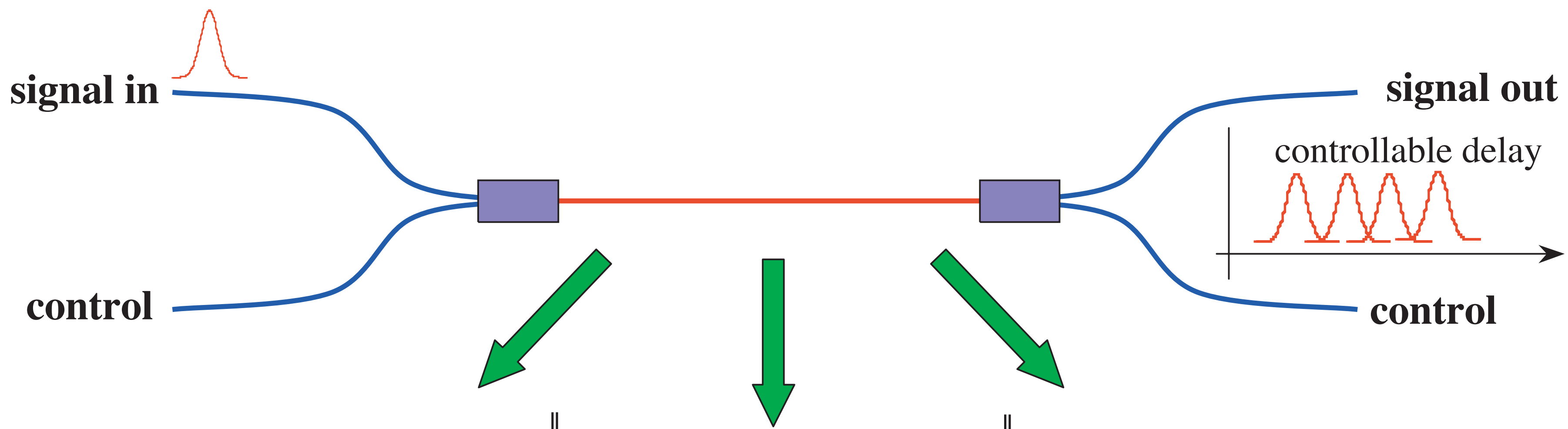
There appears to me no fundamental limitation to the maximum fractional delay achievable upon propagation (just very serious practical limitations).

- Phys. Rev. A 71 023801 (2005)

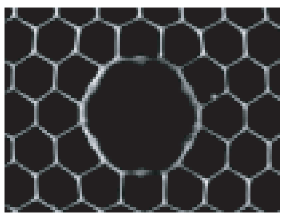
To achieve a longer fractional delay saturate deeper to propagate farther

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

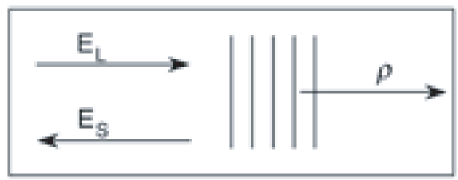
Slow-Light-Based All-Optical Tunable Delays and Buffers



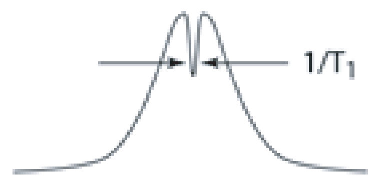
3 Approaches:



Photonic Crystal Fiber
- Utilize EIT effects in gas-filled fiber.



Stimulated Scattering
- Raman/Brillouin effect produces gain/delay.

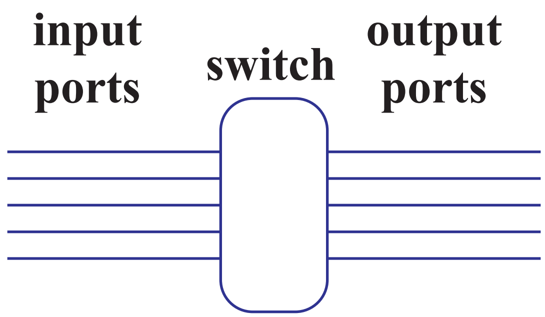


Population Oscillations
- Pumped Er-doped fiber with control beam to provide gain/delay.

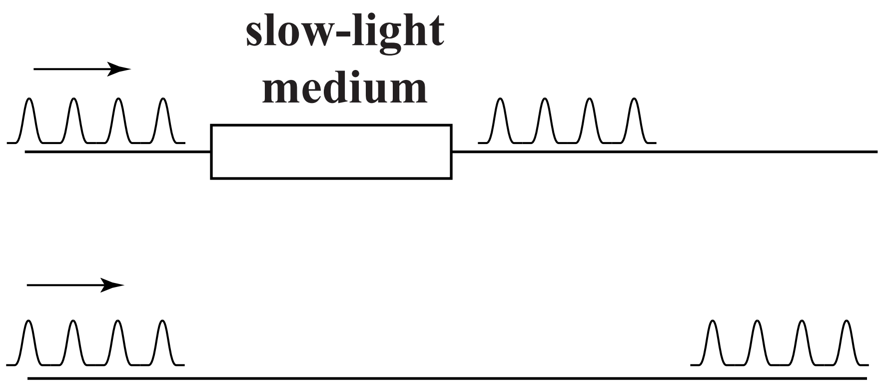
Daniel Blumenthal, UC Santa Barbara; Alexander Gaeta, Cornell University; Daniel Gauthier, Duke University; Alan Willner, University of Southern California; Robert Boyd, John Howell, University of Rochester

Slow Light and Optical Buffers

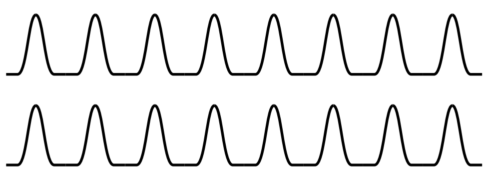
All-Optical Switch



Use of Optical Buffer for Contention Resolution



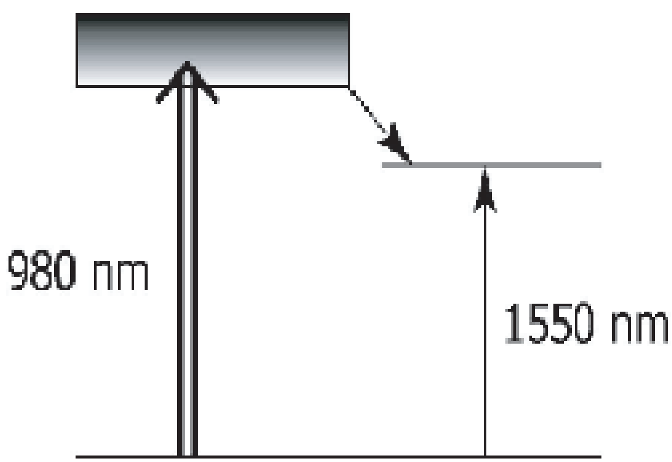
But what happens if two data packets arrive simultaneously?

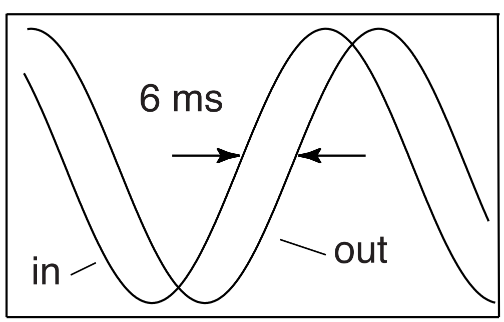


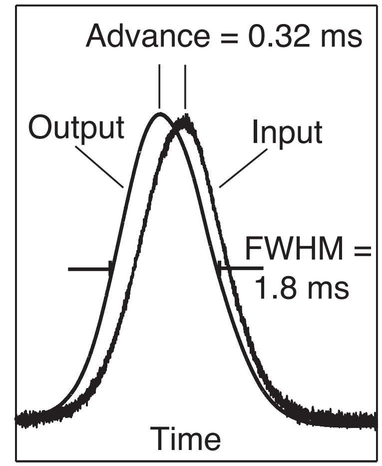
Controllable slow light for optical buffering can dramatically increase system performance.

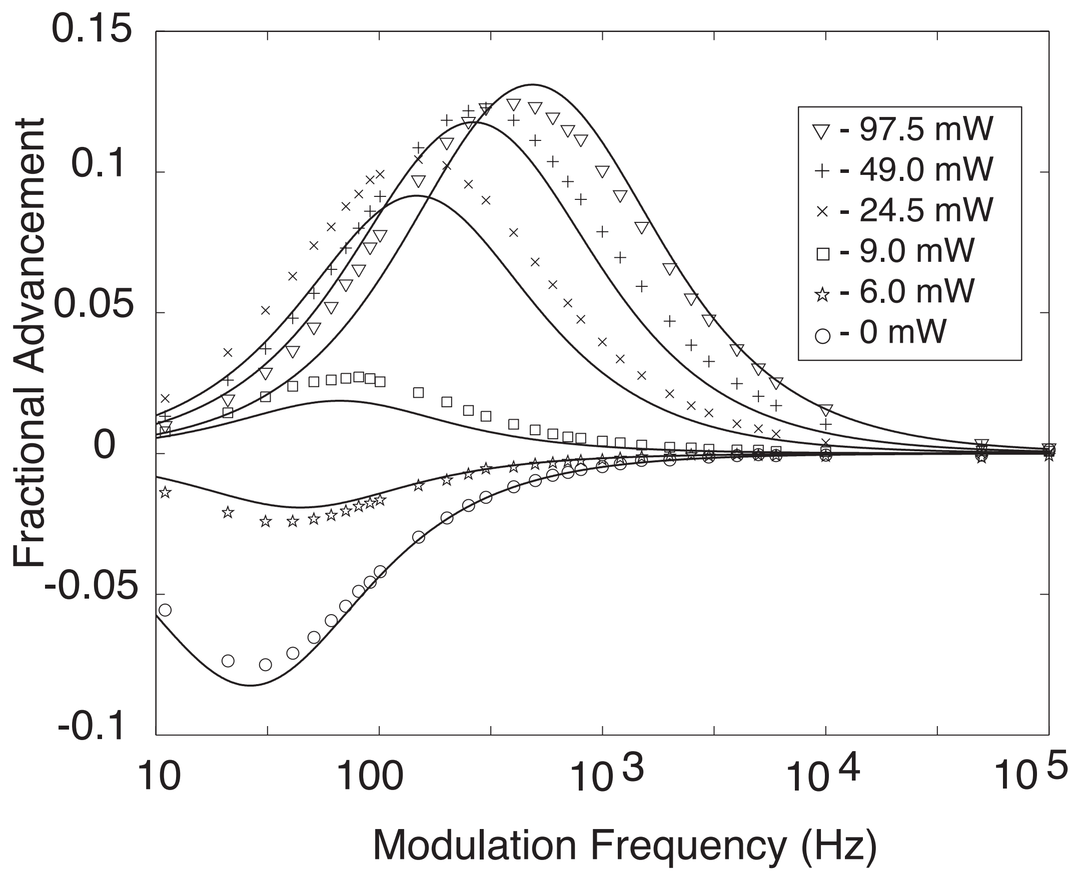
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



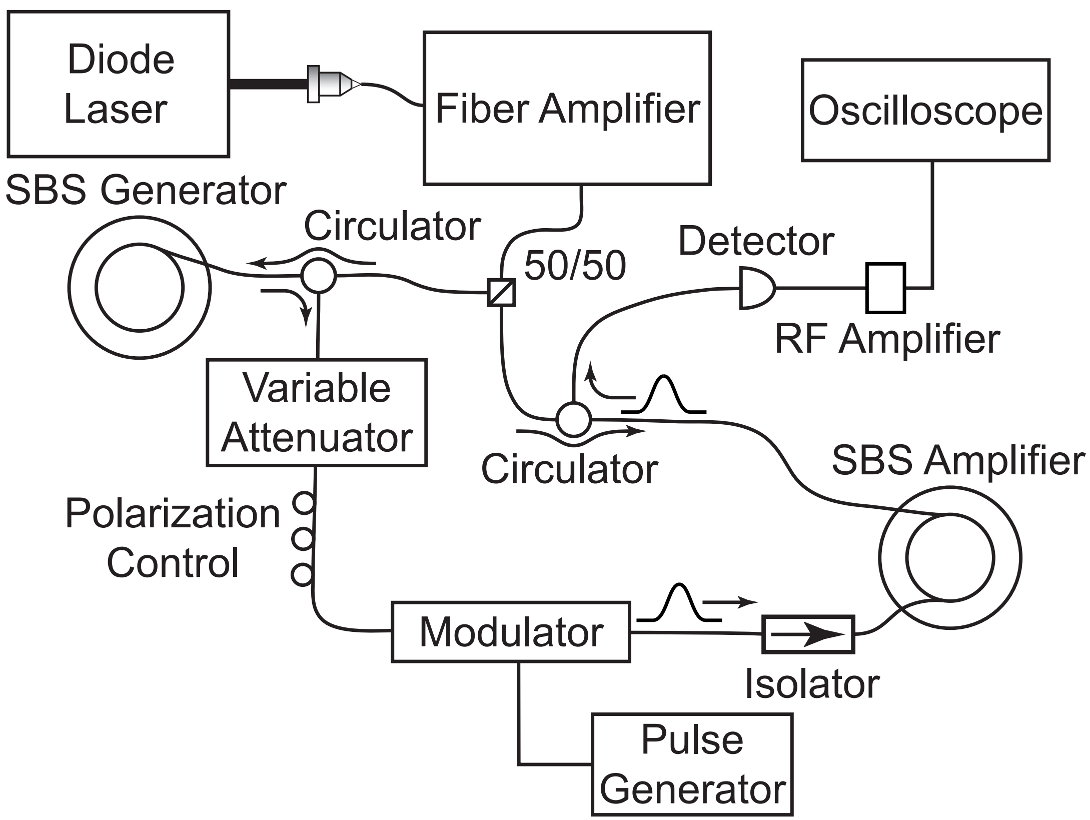




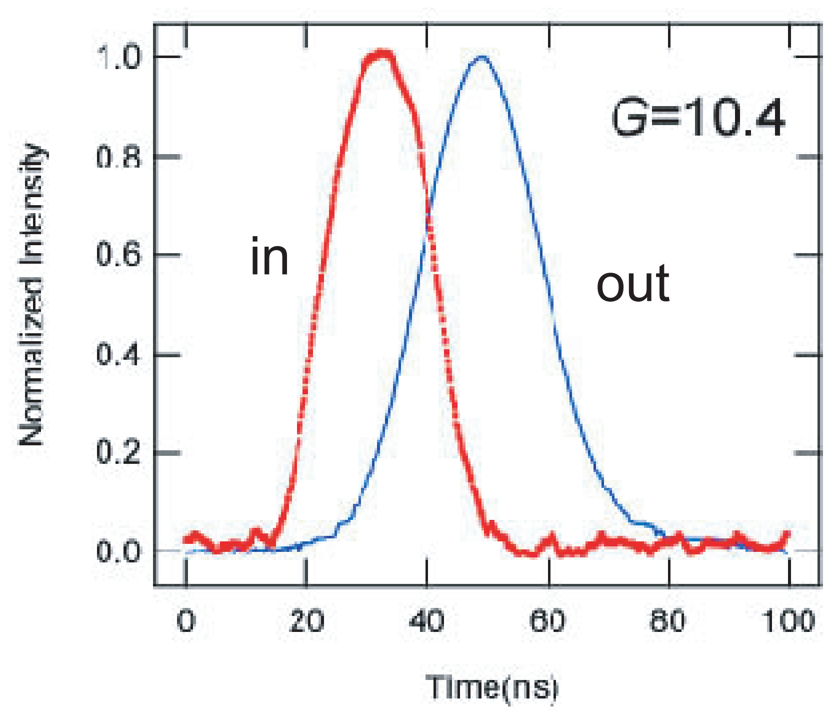


Slow-Light via Stimulated Brillouin Scattering

- Rapid spectral variation of the refractive response associated with SBS gain leads to slow light propagation
- Supports bandwidth of 100 MHz, group index of about 100
- Even faster modulation for SRS
- Joint project with Gaeta and Gauthier



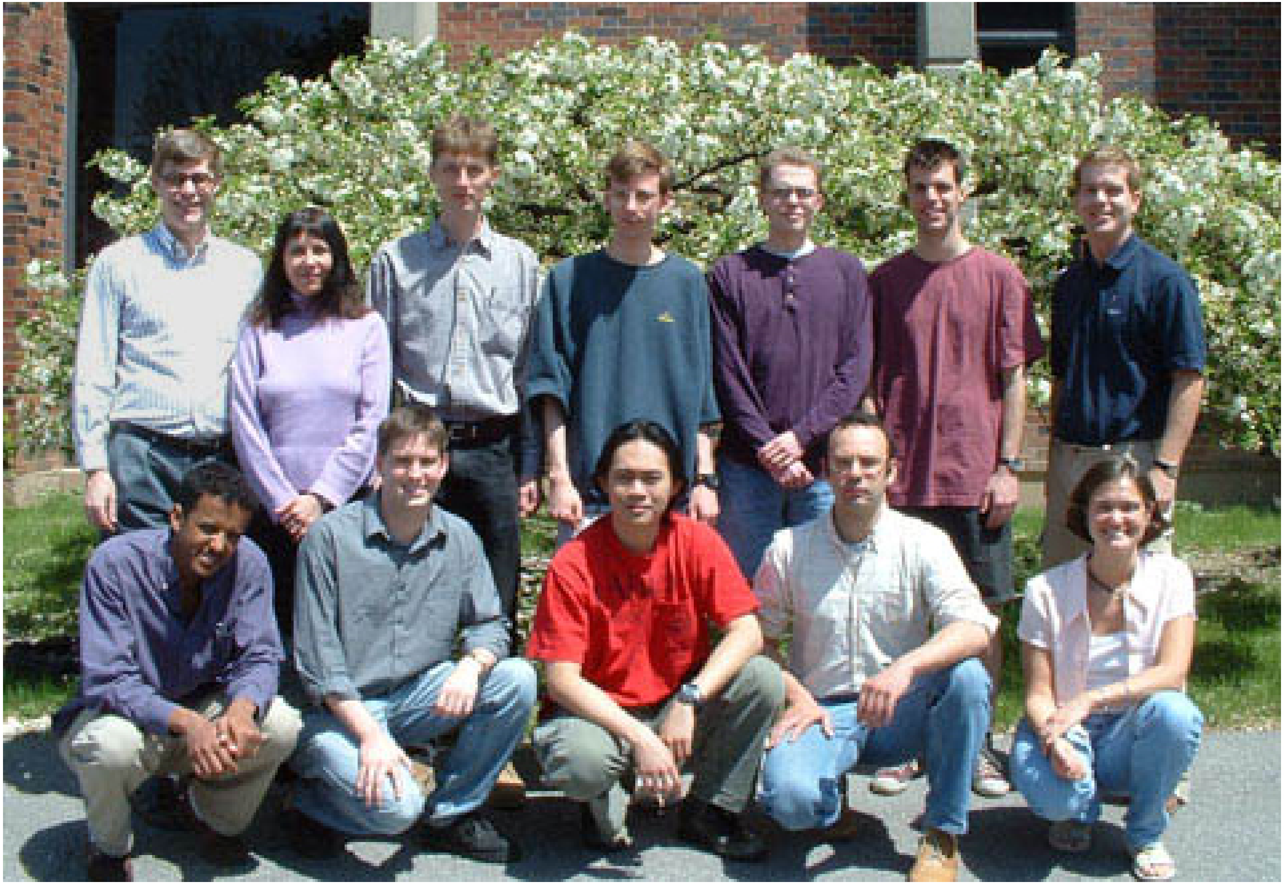
typical data



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

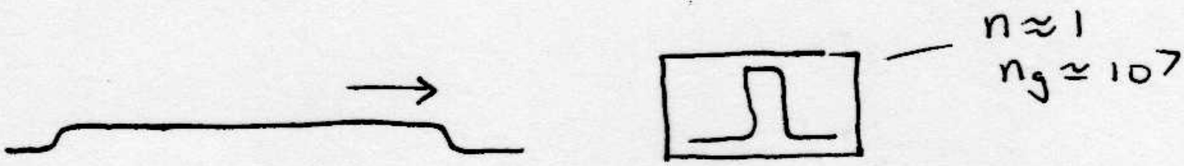
Special Thanks to my Students and Research Associates



Thank you for your attention.

And thanks to NSFand DARPA for financial support!

Kinematics of Slow Light



Pulse undergoes spatial compression by factor

$$\frac{c}{v_g} = n_g \qquad (\sim 10^7) \qquad (\text{km} \to \mu\text{m})$$

Energy density increases by same factor

$$u = \frac{1}{2} \varepsilon_0 n_g |E|^2$$

But field strength E remains constant (no discontinuity in n) as does beam power!

$$I = \frac{P}{A} = \underbrace{u\, v_g}_{} = \frac{1}{2} \varepsilon_0 c\, n\, |E|^2$$

u increases but v_g decreases.

Harris + Hau, PRL 4611 1999.