Fundamentals and Applications of Slow Light in Room Temperature Solids

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

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.

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)

Group Velocity

Pulse
(wave packet)

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

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

Thus

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

Thus $\quad n_g \neq n \quad$ in a dispersive medium!
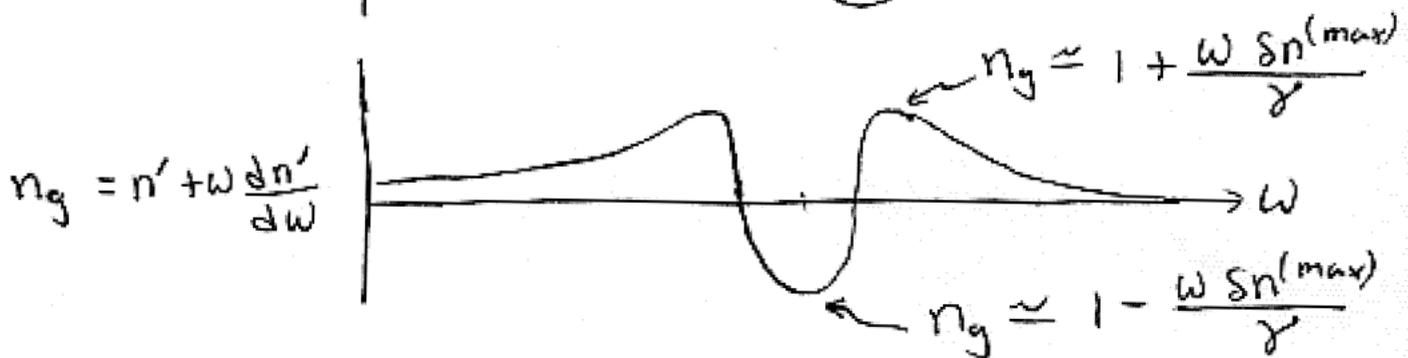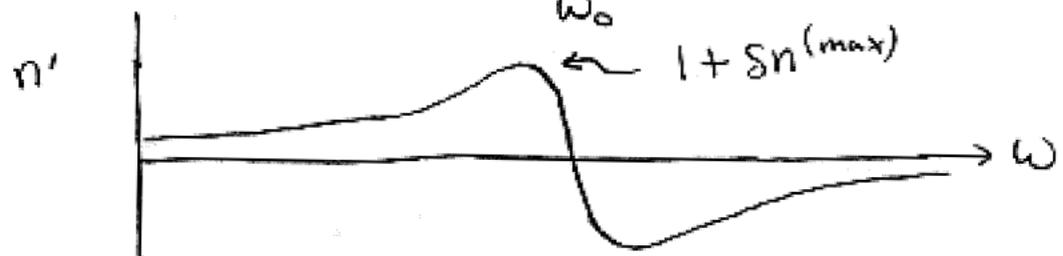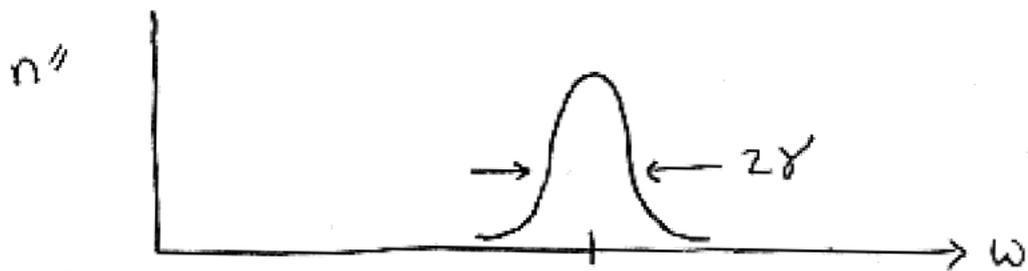
Light Propagation in Atomic Vapors

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

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

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

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

$$\frac{\omega \, \delta n^{(max)}}{\gamma} \approx \frac{2\pi(5 \times 10^{14})(0.1)}{2\pi(1 \times 10^9)} = 5 \times 10^4 \sim (!)$$

n_g can range from $+5 \times 10^4$ 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 (EIT, CPT), 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*§

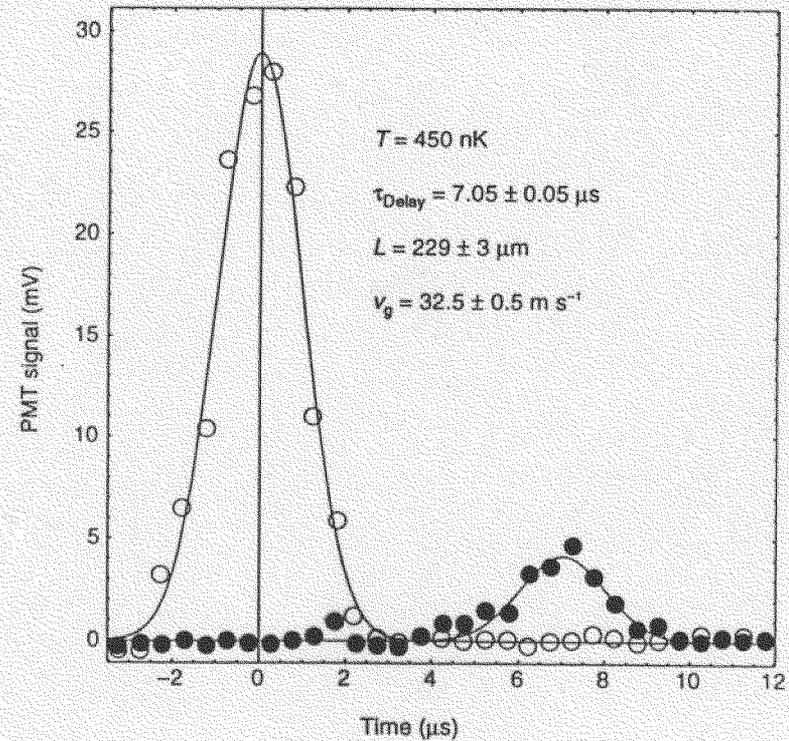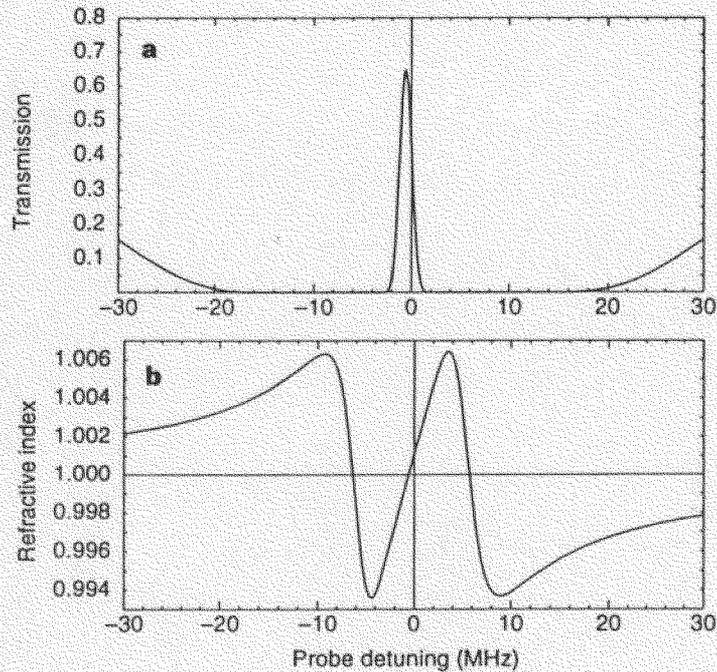* Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge,
Massachusetts 02142, USA
† Department of Physics, § Division of Engineering and Applied Sciences,
Harvard University, Cambridge, Massachusetts 02138, USA
‡ Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305,
USA
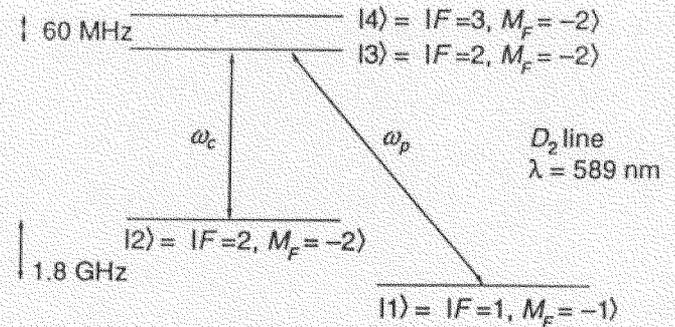
$$\nu_g = \frac{c}{n(\omega_p) + \omega_p \dfrac{dn}{d\omega_p}} \approx \frac{\hbar c \epsilon_0}{2\omega_p} \frac{|\Omega_c|^2}{|\mu_{13}|^2 N}$$

Challenge/Goal

Slow light in 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
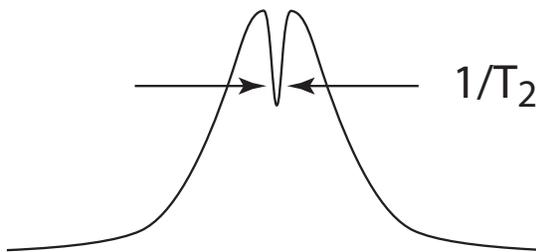
Need a large $dn/d\omega$. (How?)

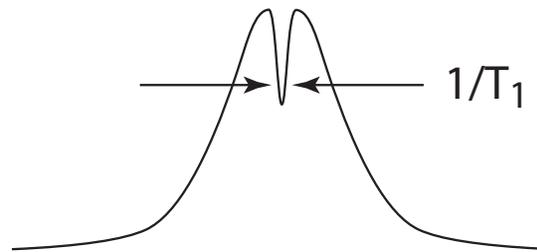Kramers-Kronig relations:
   Want a very narrow absorption line.

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

Make use of "spectral holes" due to population oscillations.

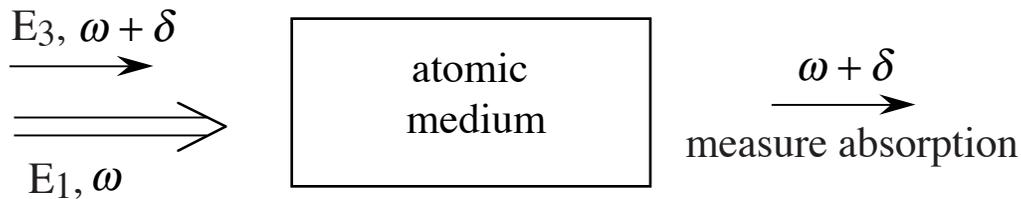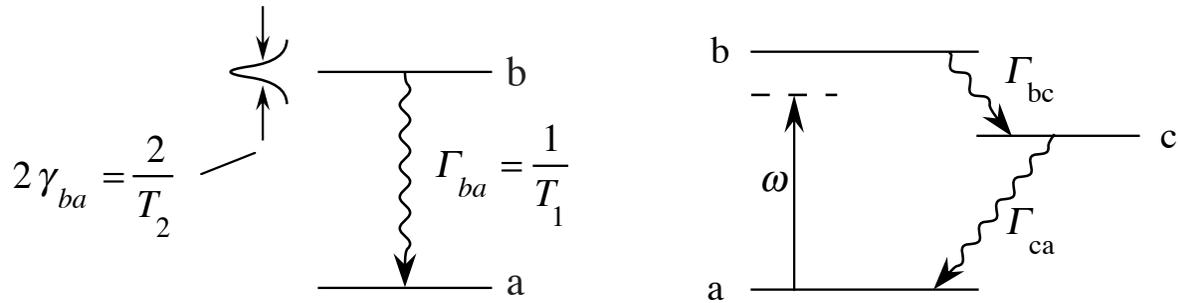Hole-burning in a homogeneously broadened line; requires $T_2 \ll T_1$.

inhomogeneously
broadened medium

homogeneously
broadened medium
(or inhomogeneously
broadened)

Spectral Holes Due to Population Oscillations

$$2\gamma_{ba} = \frac{2}{T_2} \qquad \Gamma_{ba} = \frac{1}{T_1}$$

E₃, $\omega + \delta$ → ⇒ E₁, ω → [atomic medium] → $\omega + \delta$ → measure absorption

Population inversion:

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

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

Probe-beam response:

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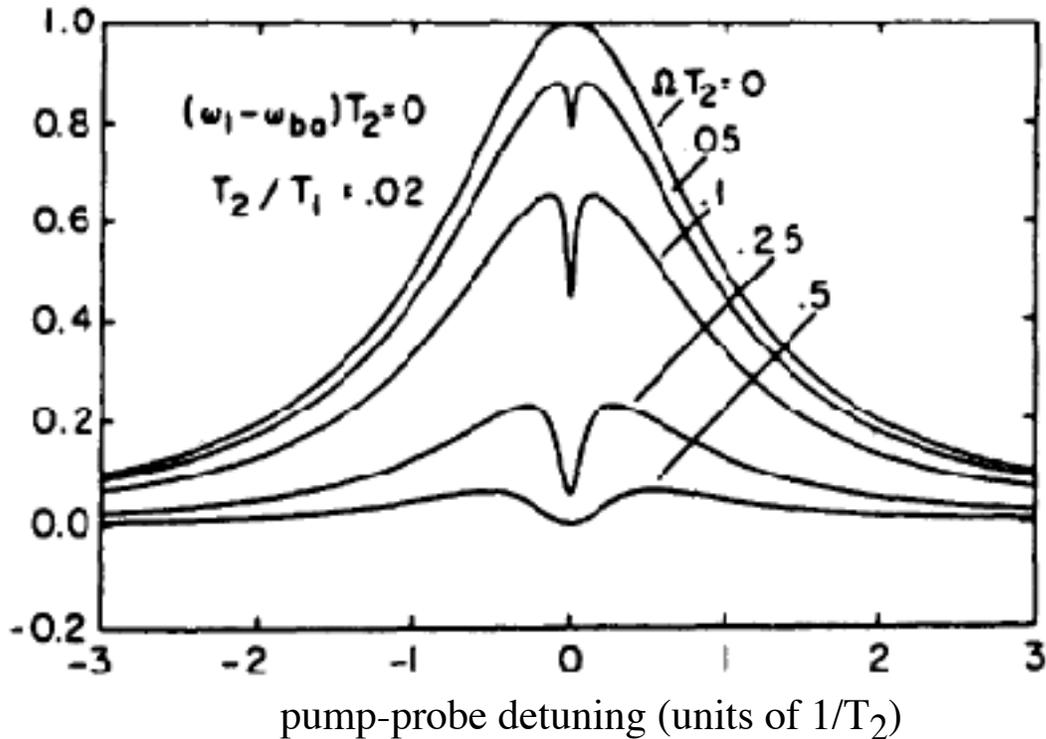
Probe-beam absorption:

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

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 ($T_2 \ll T_1$)


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.

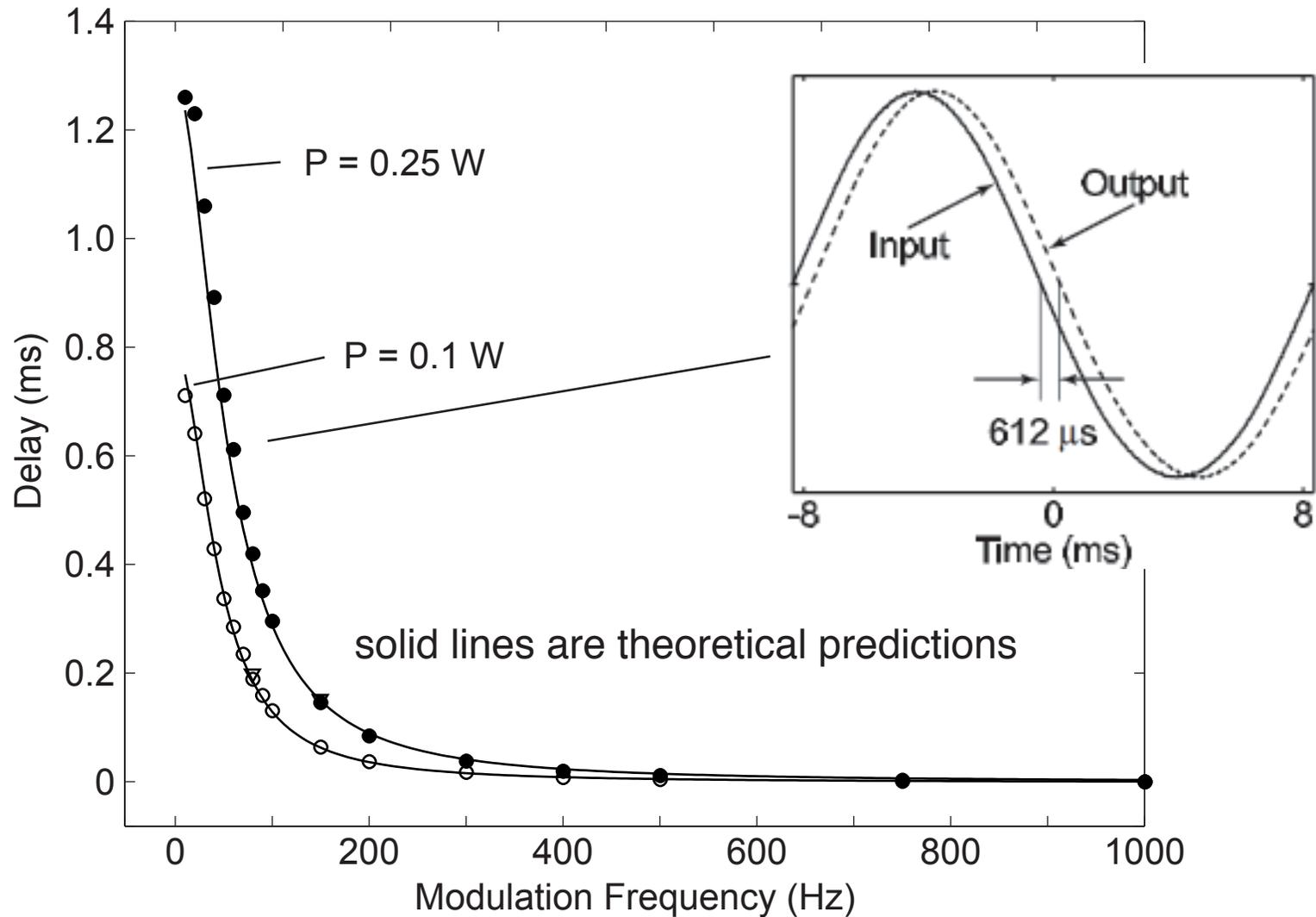*The Institute of Optics, University of Rochester, Rochester, NY 14627, USA*
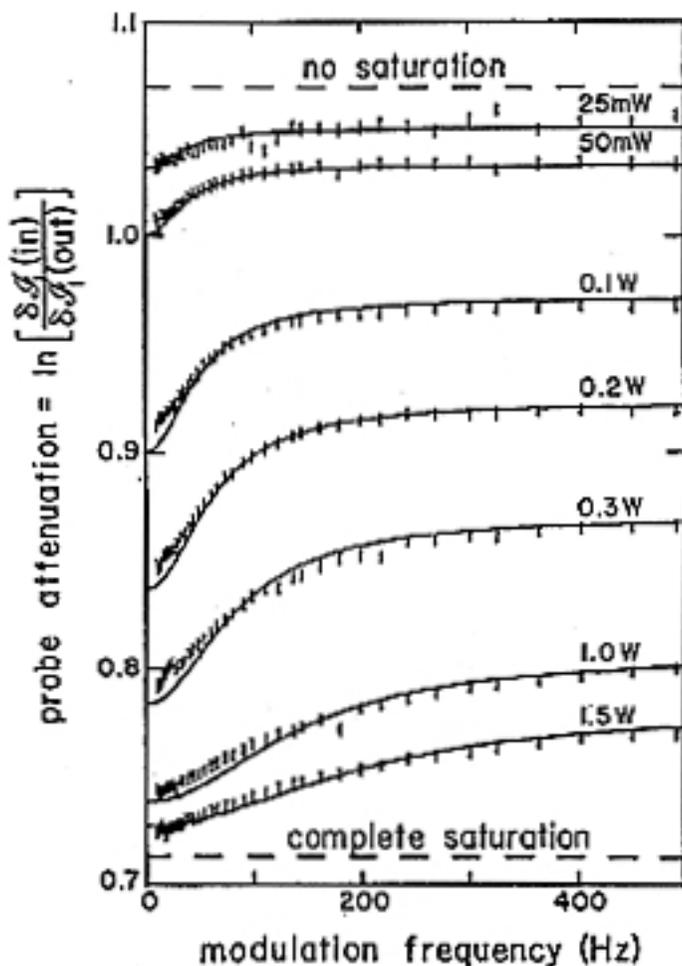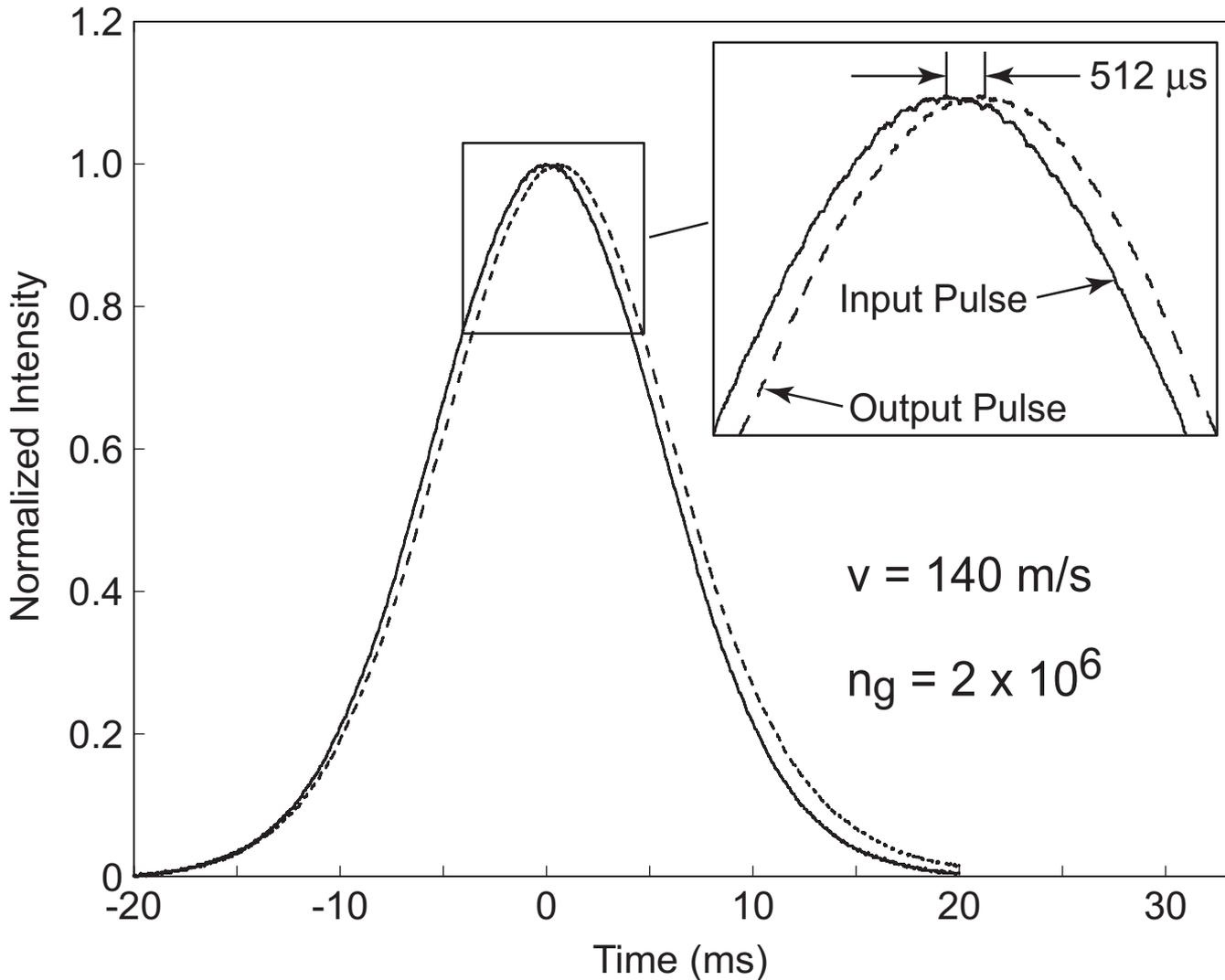
Slow Light Experimental Setup
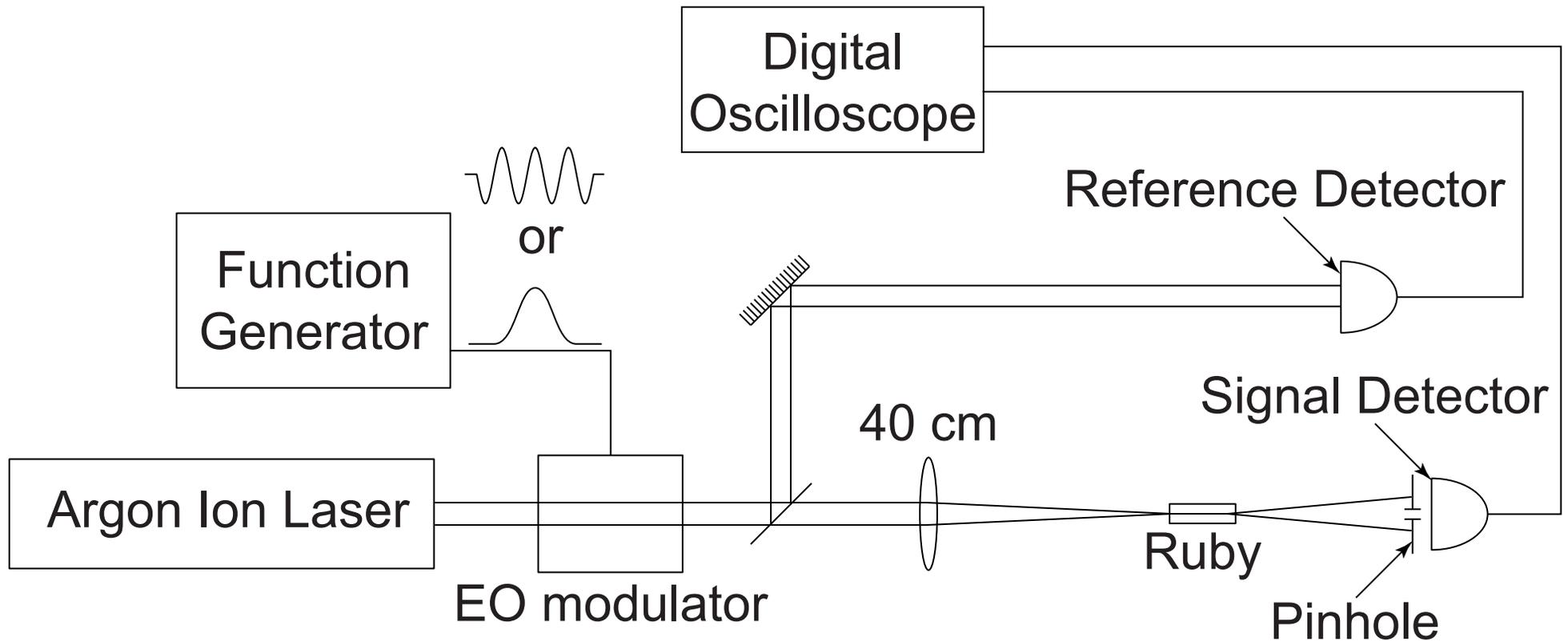
7.25-cm-long ruby laser rod (pink ruby)

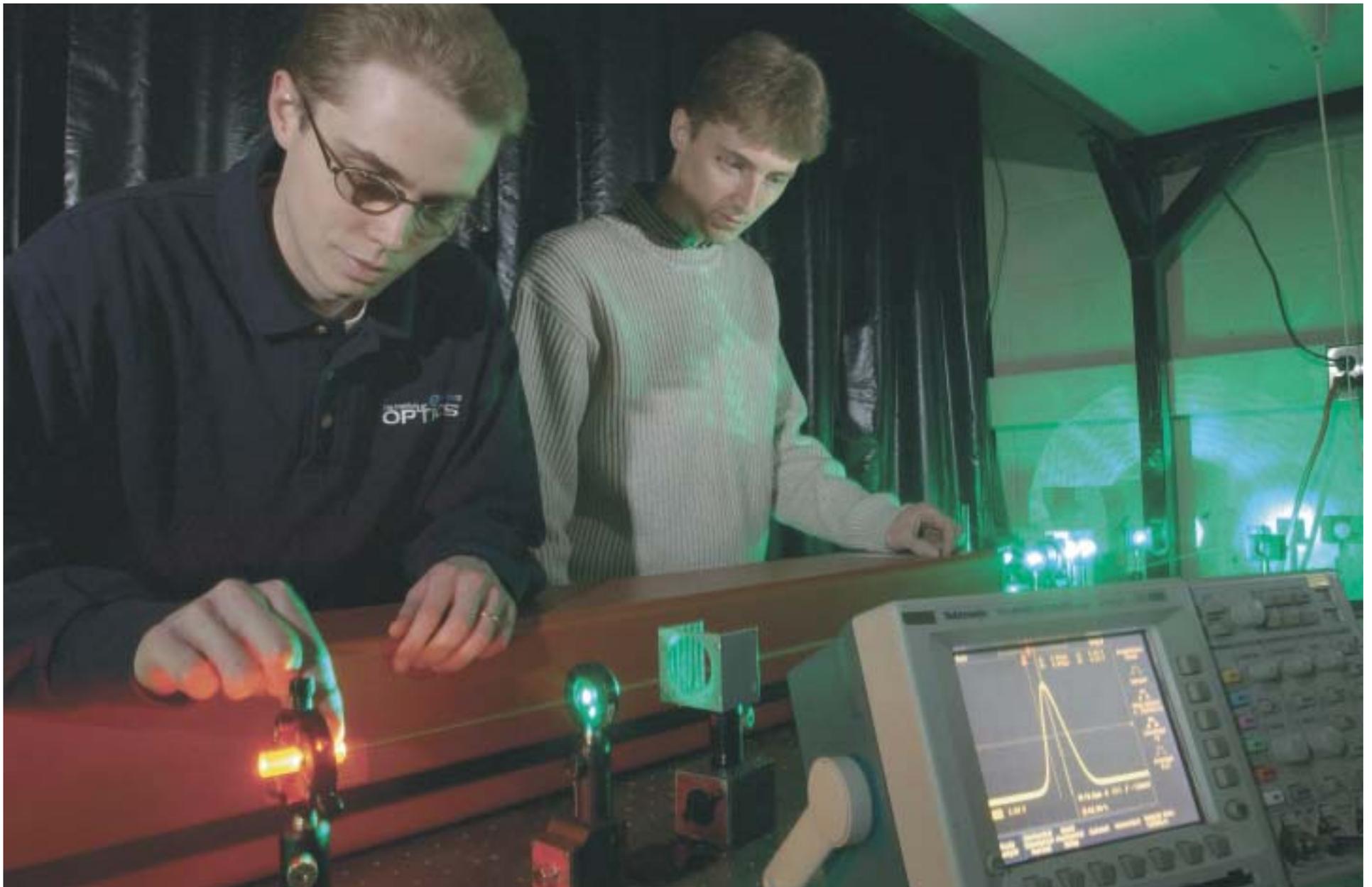# Measurement of Delay Time for Harmonic Modulation

solid lines are theoretical predictions

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

Gaussian Pulse Propagation Through Ruby
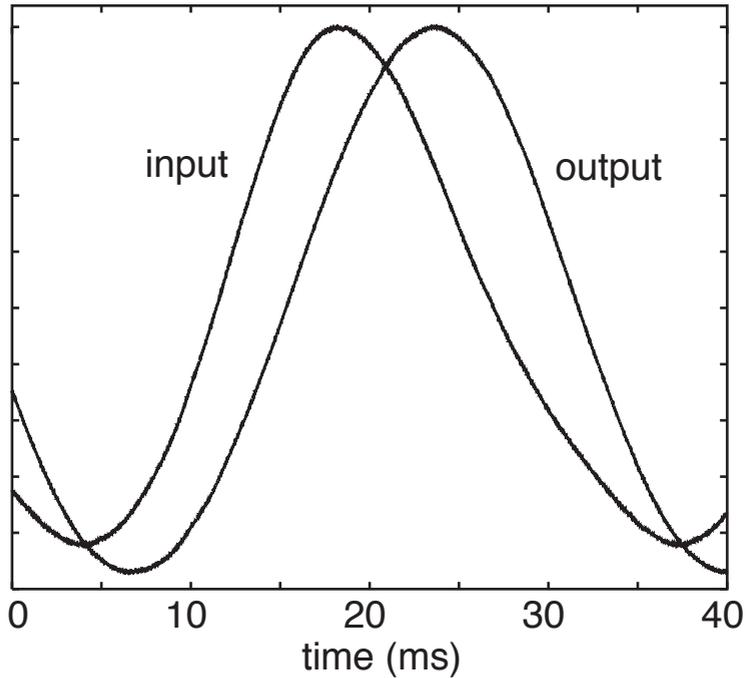

No pulse distortion!

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
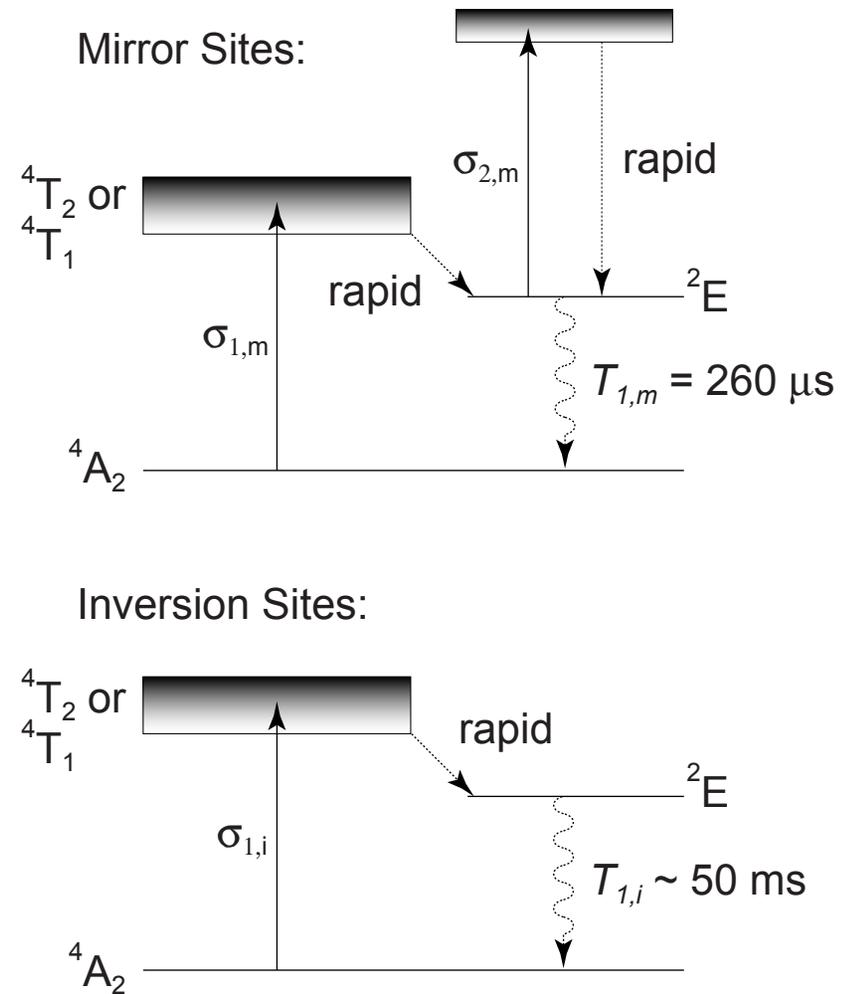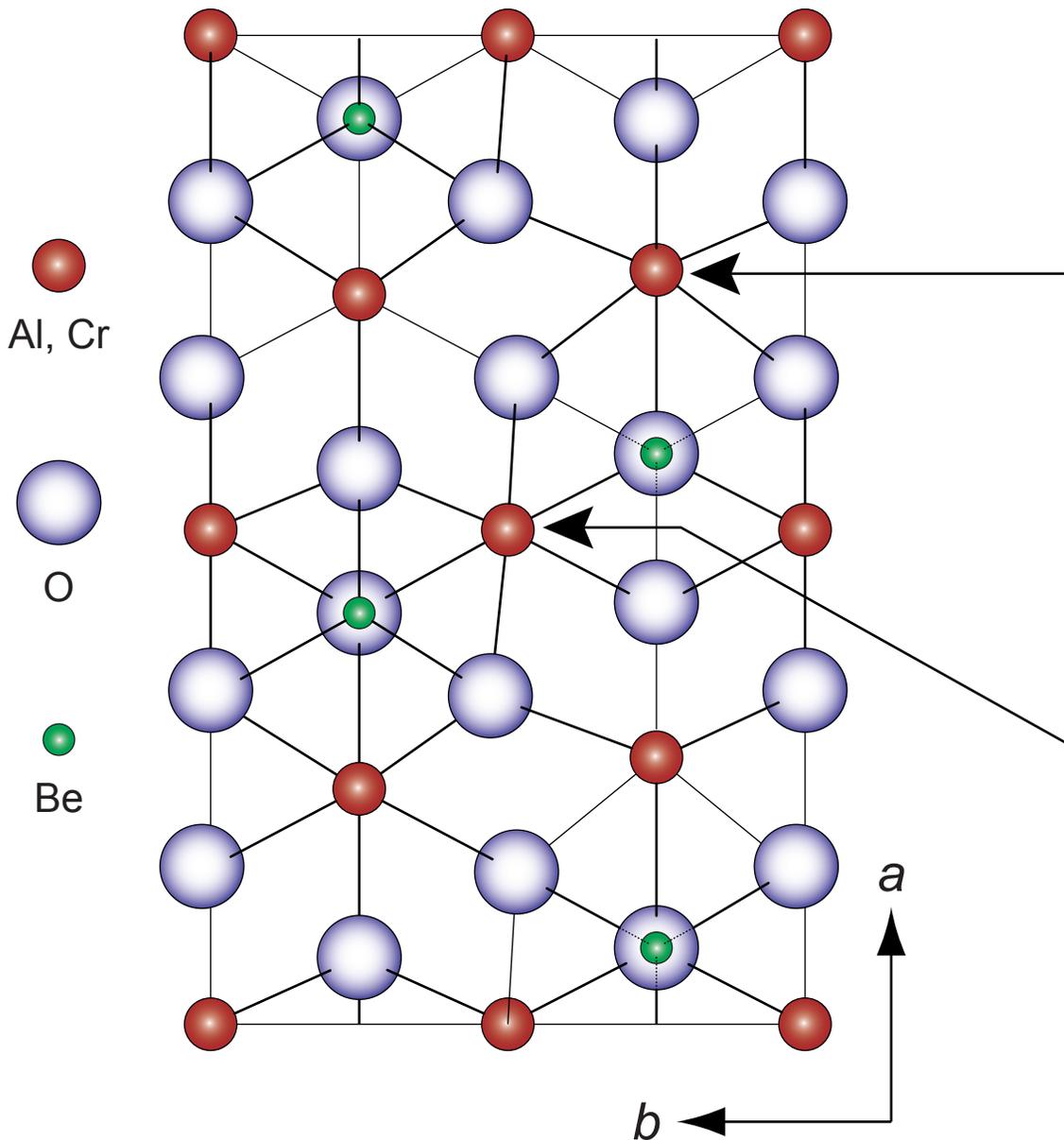
Works in solids

Works at room temperature

Insensitive of dephasing processes

Laser need not be frequency stabilized

Works with single beam (self-delayed)

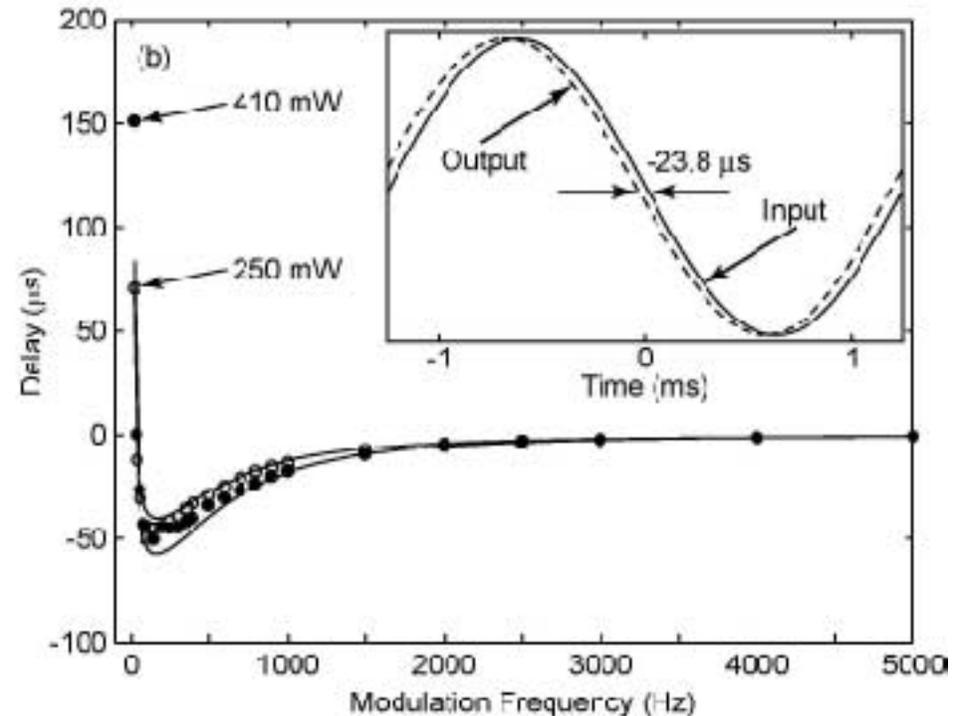**Delay can be controlled through input intensity**
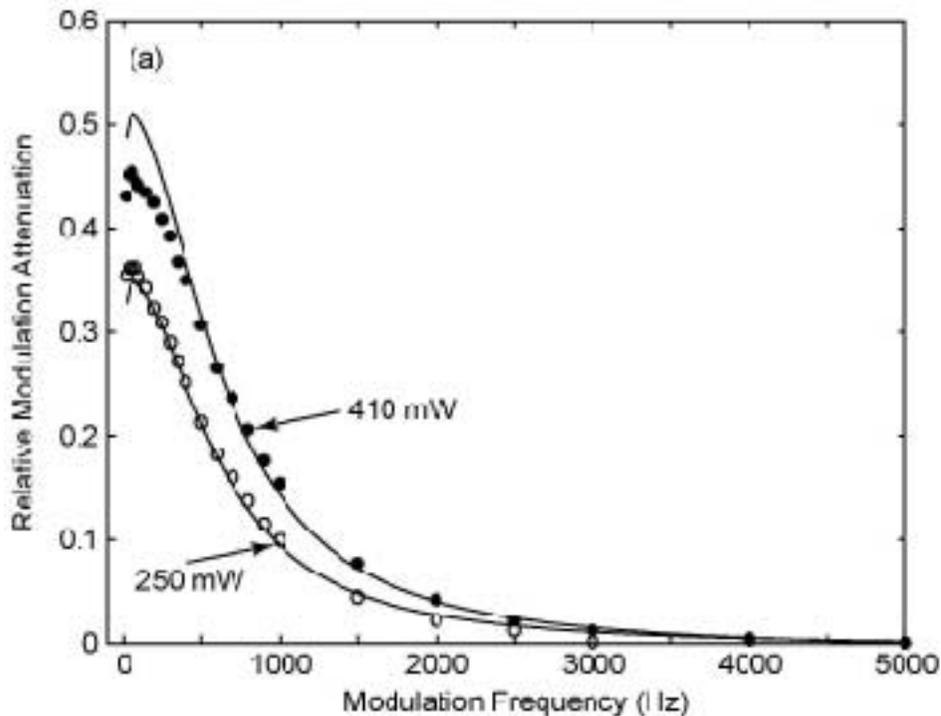
Alexandrite Displays both Saturable and Inverse-Saturable Absorption

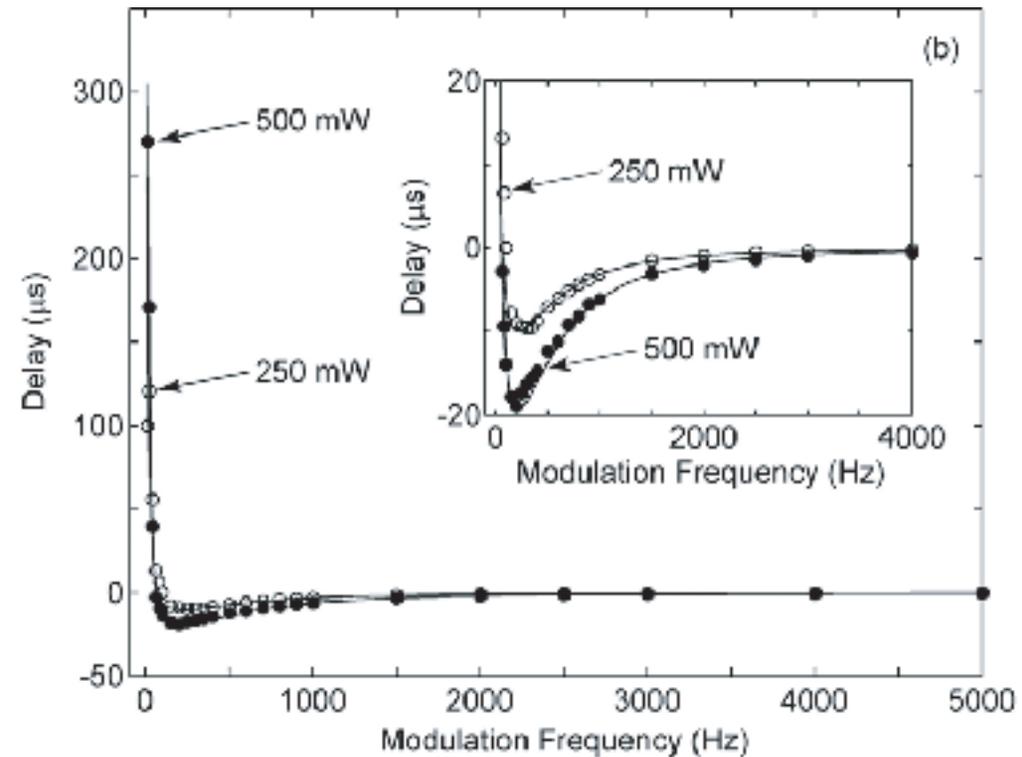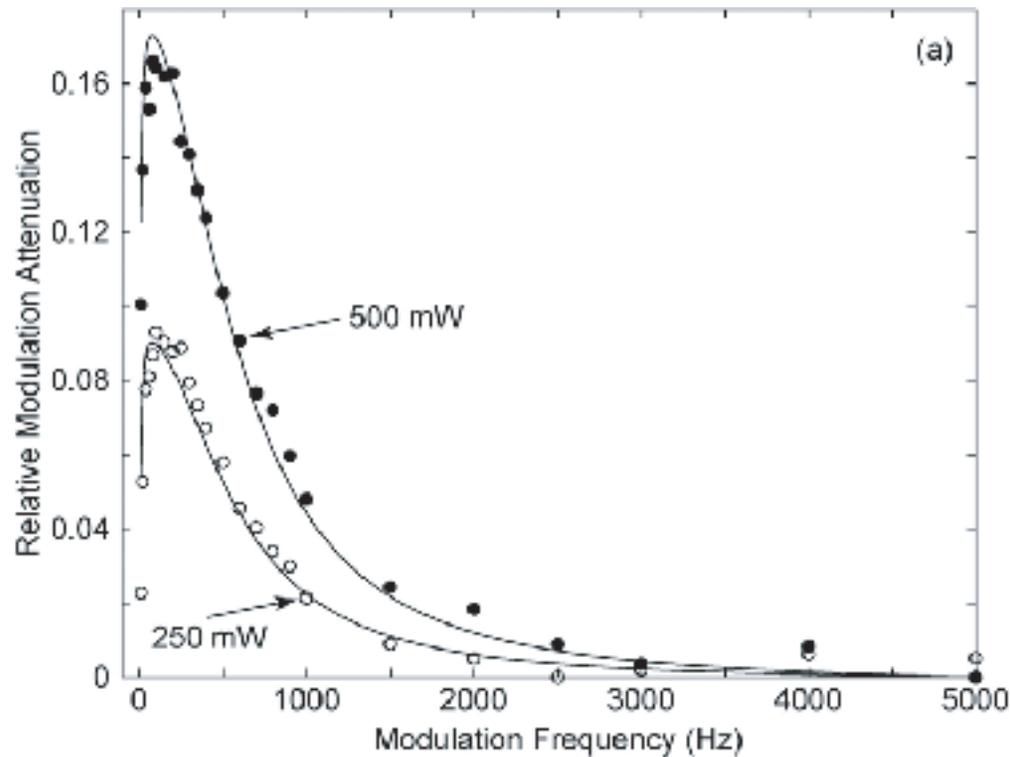# Inverse-Saturable Absorption Produces Superluminal Propagation in Alexandrite

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

Probe Absorption and Delay at 488 nm

Hole at low frequencies, anti-hole at larger frequencies leads to slow light for long pulses and fast light for shorter pulses.
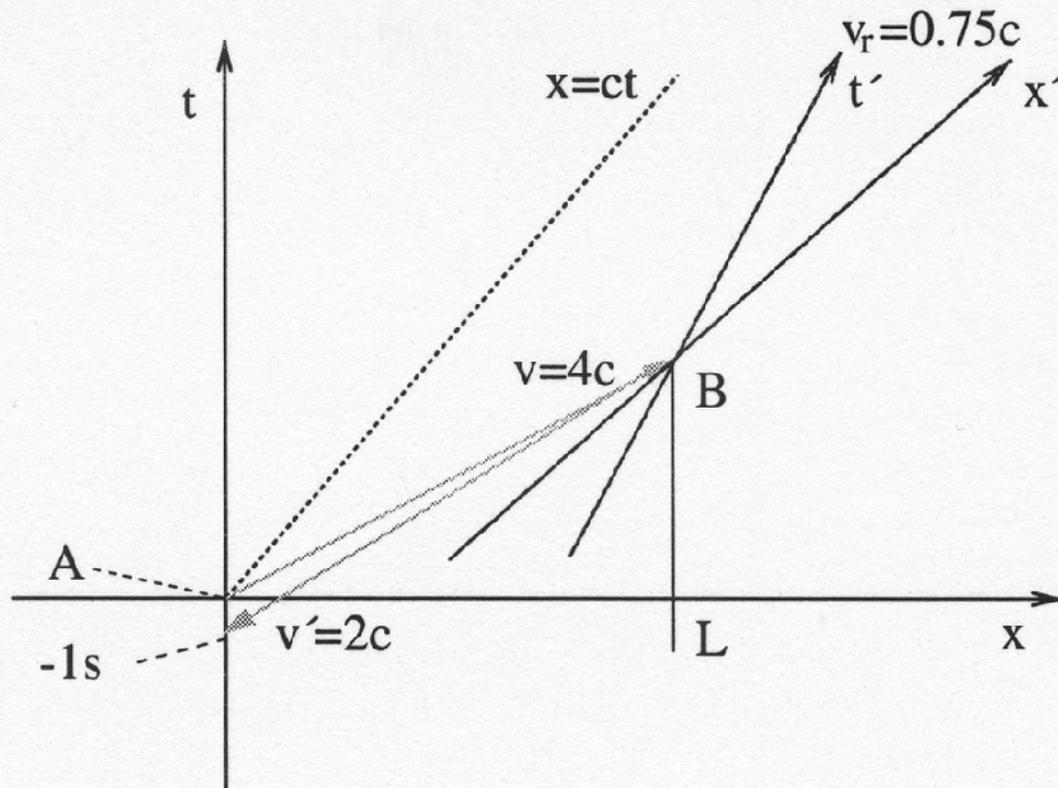
Causality and Superluminality

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?

What is the velocity at which information is transmitted?

- ## What is a signal?

  Brillouin: *A <u>signal</u> is a short isolated succession of wavelets, with the system at rest before the signal arrived and also after it has passed.*   L. Brillouin (1960), p. 7.

  Finite Duration = Infinite Spectrum!

- ## What is information (or signal) velocity?

  Brillouin:

        Normal Dispersion: $v_s = v_g$
        Anomalous Dispersion: $v_s \leq c$

  Sommerfeld: *It can be proven that the signal velocity is exactly equal to c if we assume the observer to be equipped with a detector of infinite sensitivity, and this is true for normal or anomalous dispersion, for isotropic or anisotropic medium, that may or may not contain conduction electrons.*

Information Velocity in a Fast Light Medium
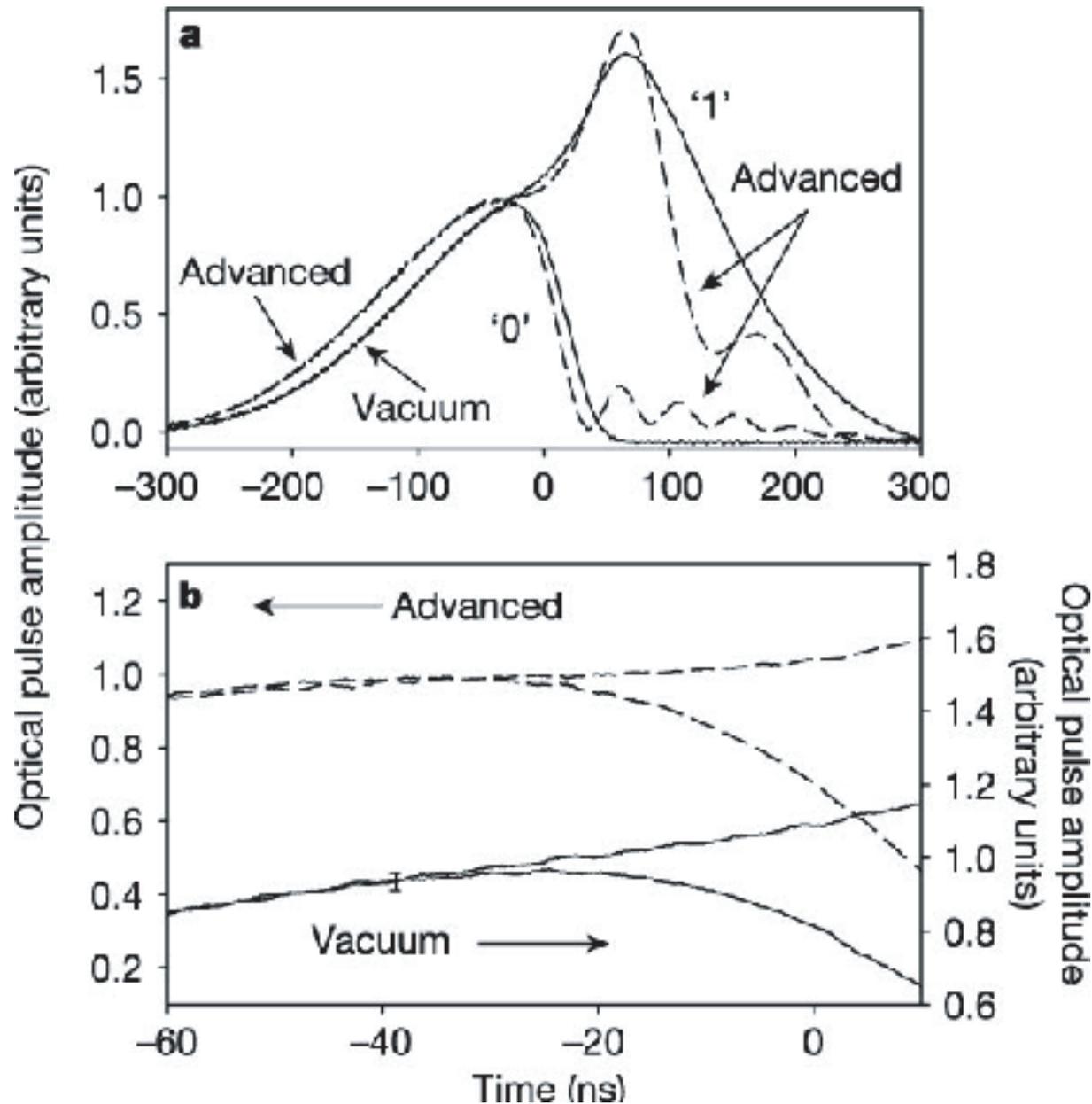
M.D. Stenner, D.J. Gauthier, and M.I. Neifeld, Nature,425 695 (2003).

Pulses are not distinguishable "early."
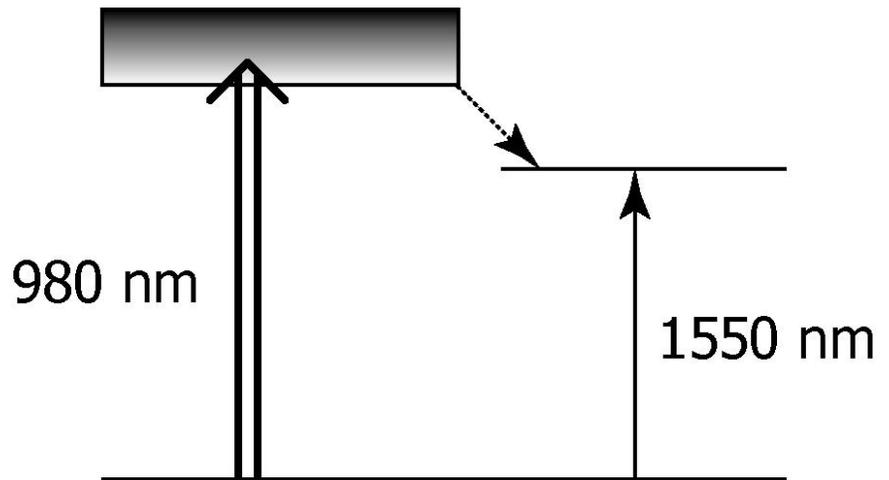
$v_i \leq c$

Slow and Fast Light --What Next?

Longer fractional delay
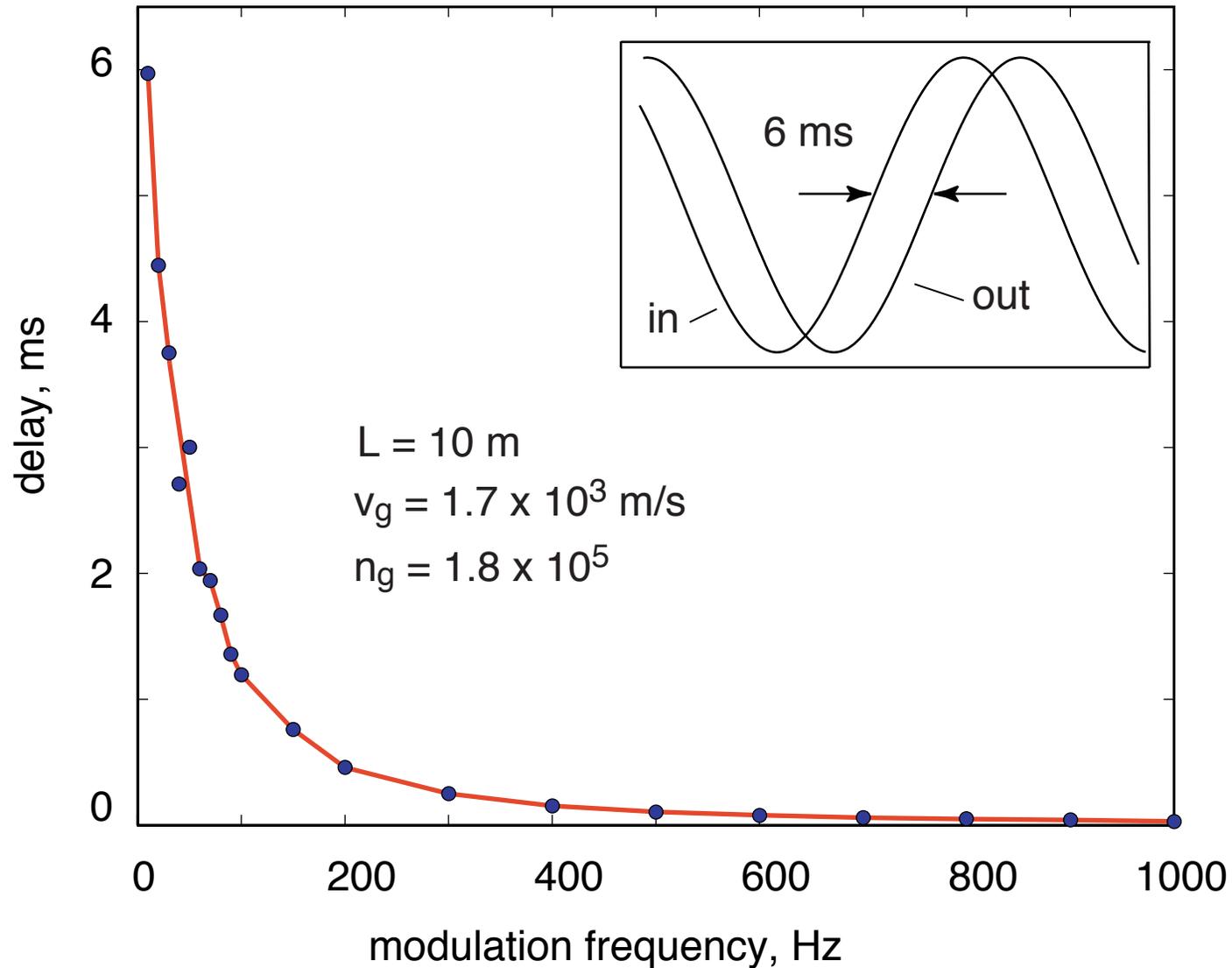 (saturate deeper; propagate farther)

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

Slow and Fast Light in a Er-doped Fiber Amplifier

- Signal at 1550 nm.
- Separate Pump and Probe Lasers.
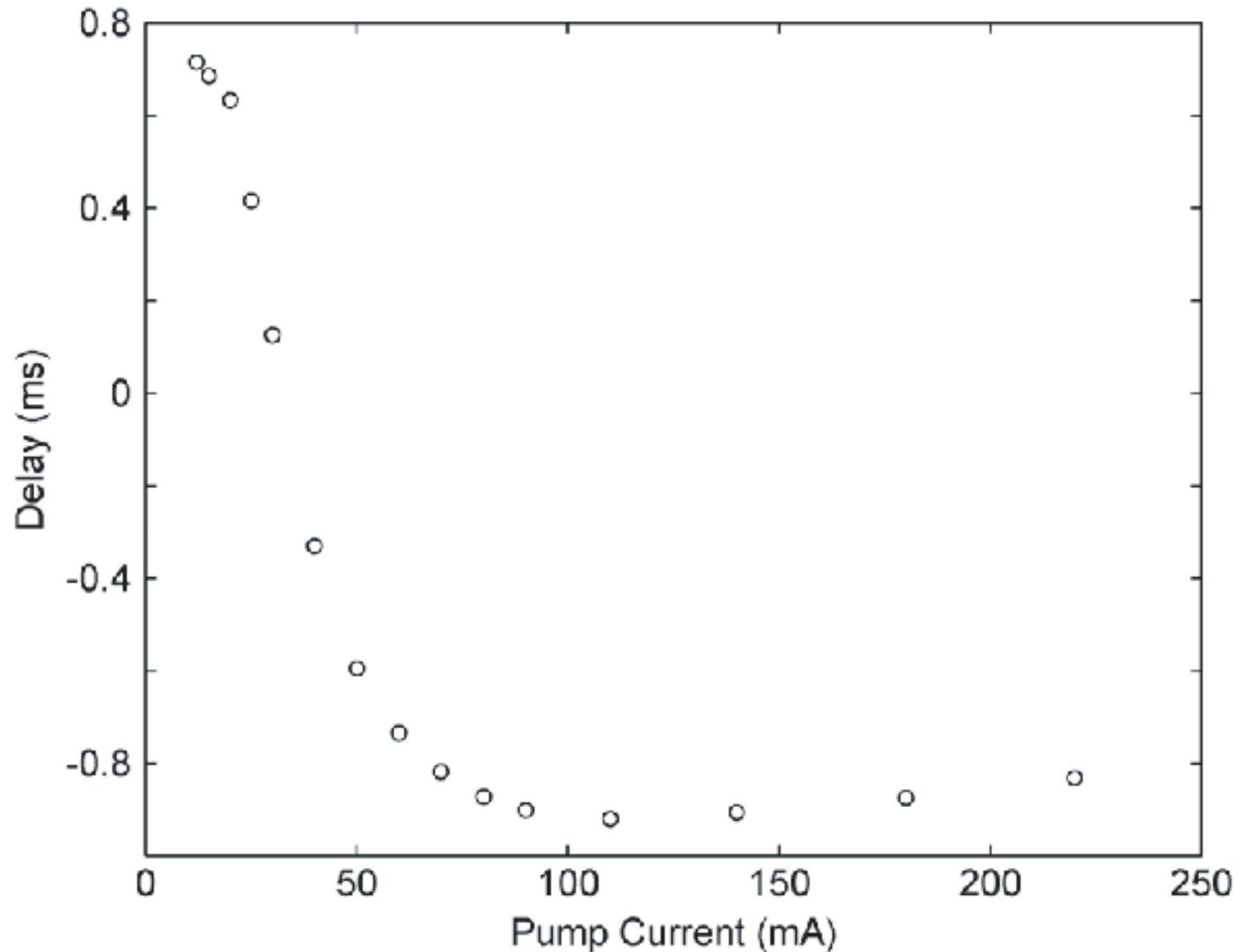- Longer Interaction Lengths.

980 nm

1550 nm

24

Slow Light in an Erbium-Doped Fiber Amplifier

L = 10 m

$v_g = 1.7 \times 10^3$ m/s

$n_g = 1.8 \times 10^5$

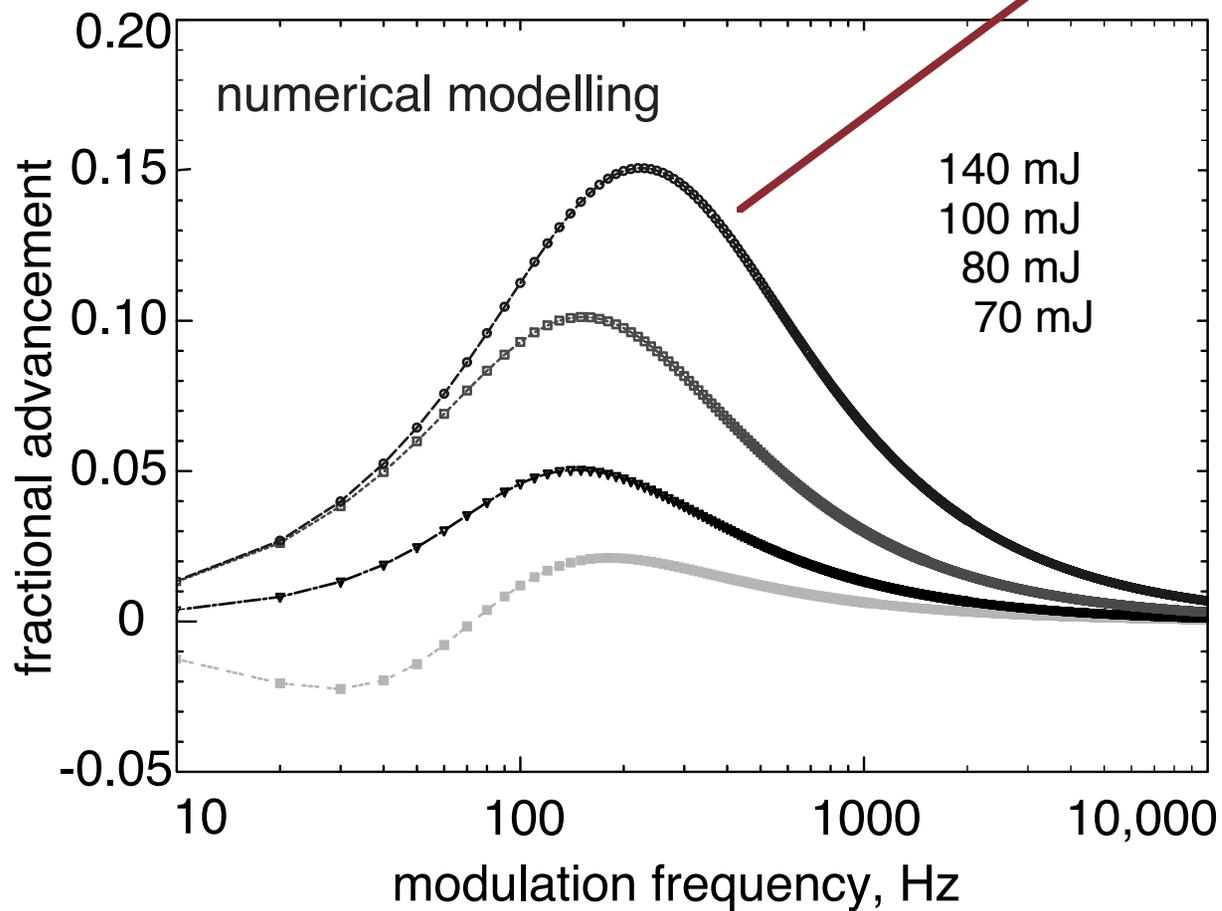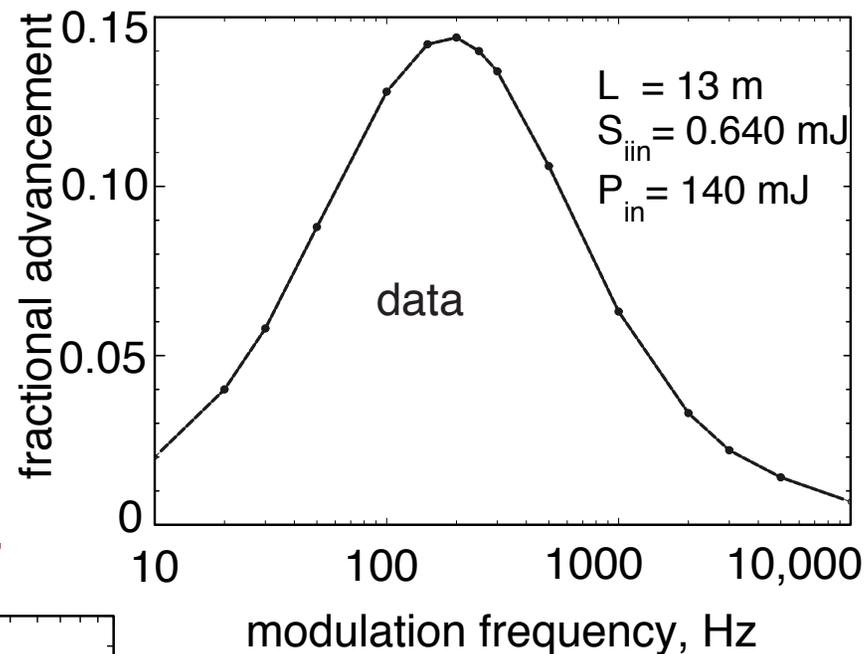with S. Jarabo, University of Zaragoza

Pump Power Dependence of Time Delay

Delay at 100 Hz for different pump currents; constant signal power.

Modelling Slow and Fast Light in Erbium

data

L = 13 m
S_{iin} = 0.640 mJ
P_{in} = 140 mJ

fractional advancement

modulation frequency, Hz

numerical modelling

140 mJ
100 mJ
80 mJ
70 mJ

fractional advancement
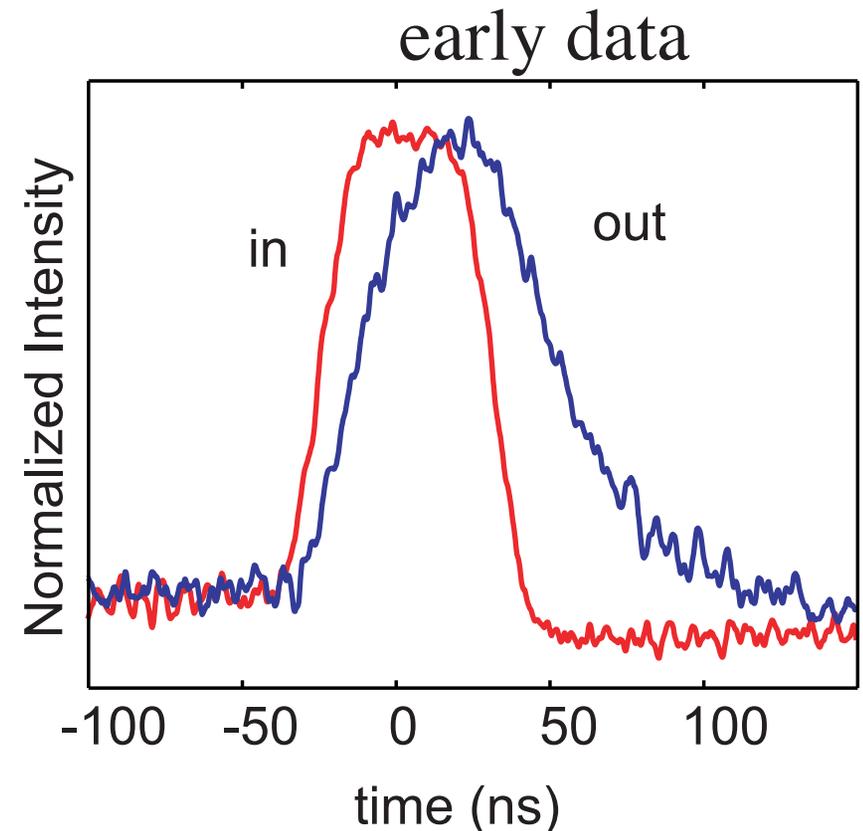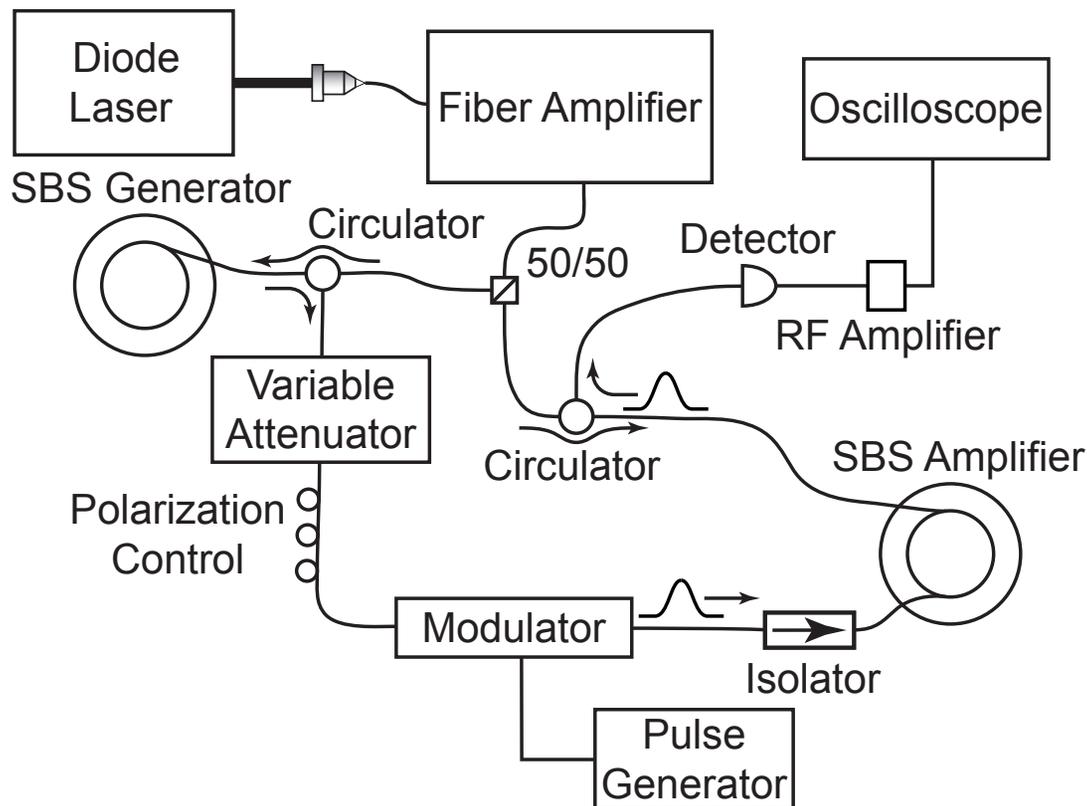
modulation frequency, Hz
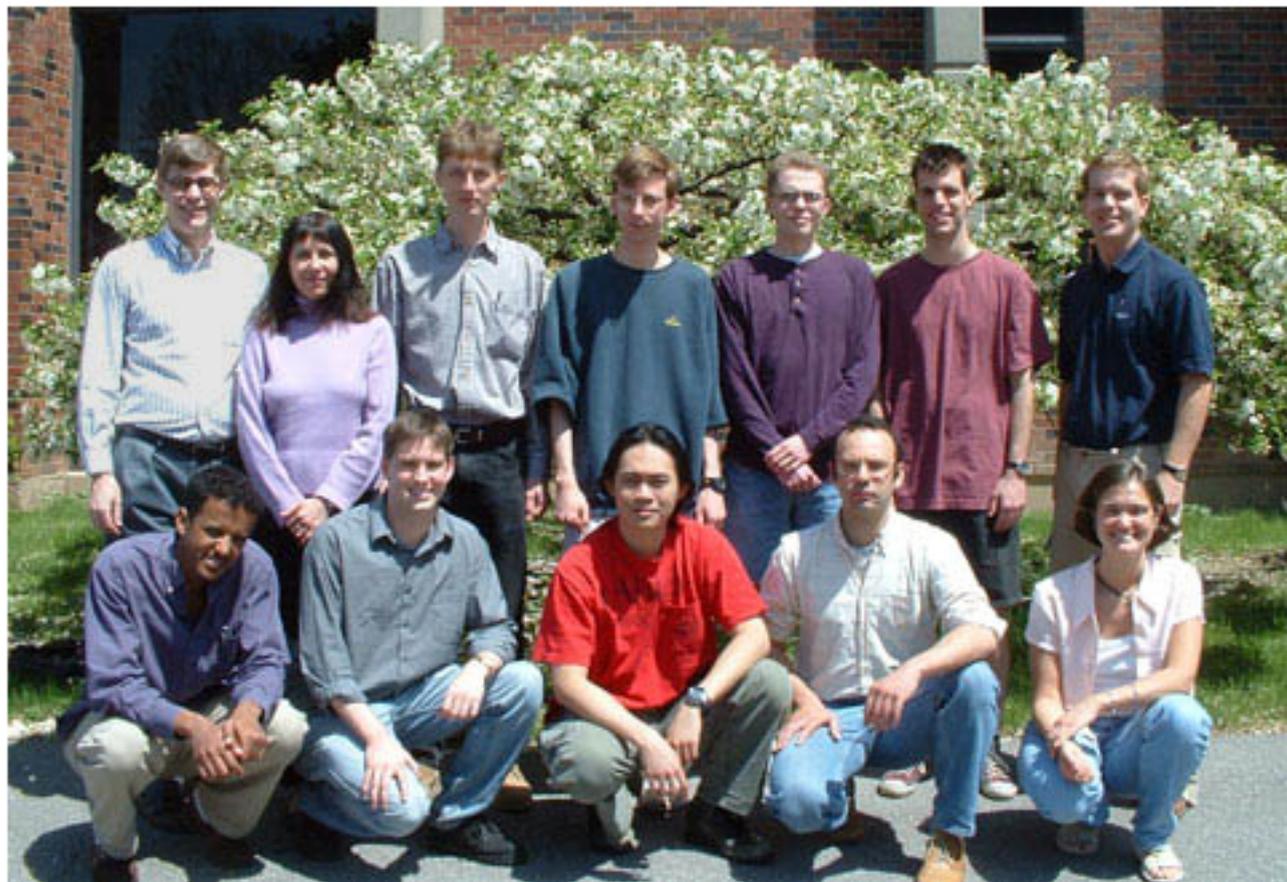
Slow-Light via Stimulated Brillouin Scattering

- 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

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.