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

Presented at the OSA Topical Meeting on Nonlinear Optics, Waikoloa, Hawaii, Augest 2-6, 2004.

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)

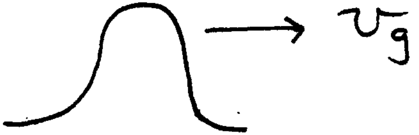
  e.g., electromagnetically induced transparency

- 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 $v_g = \frac{d\omega}{dk}$

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!

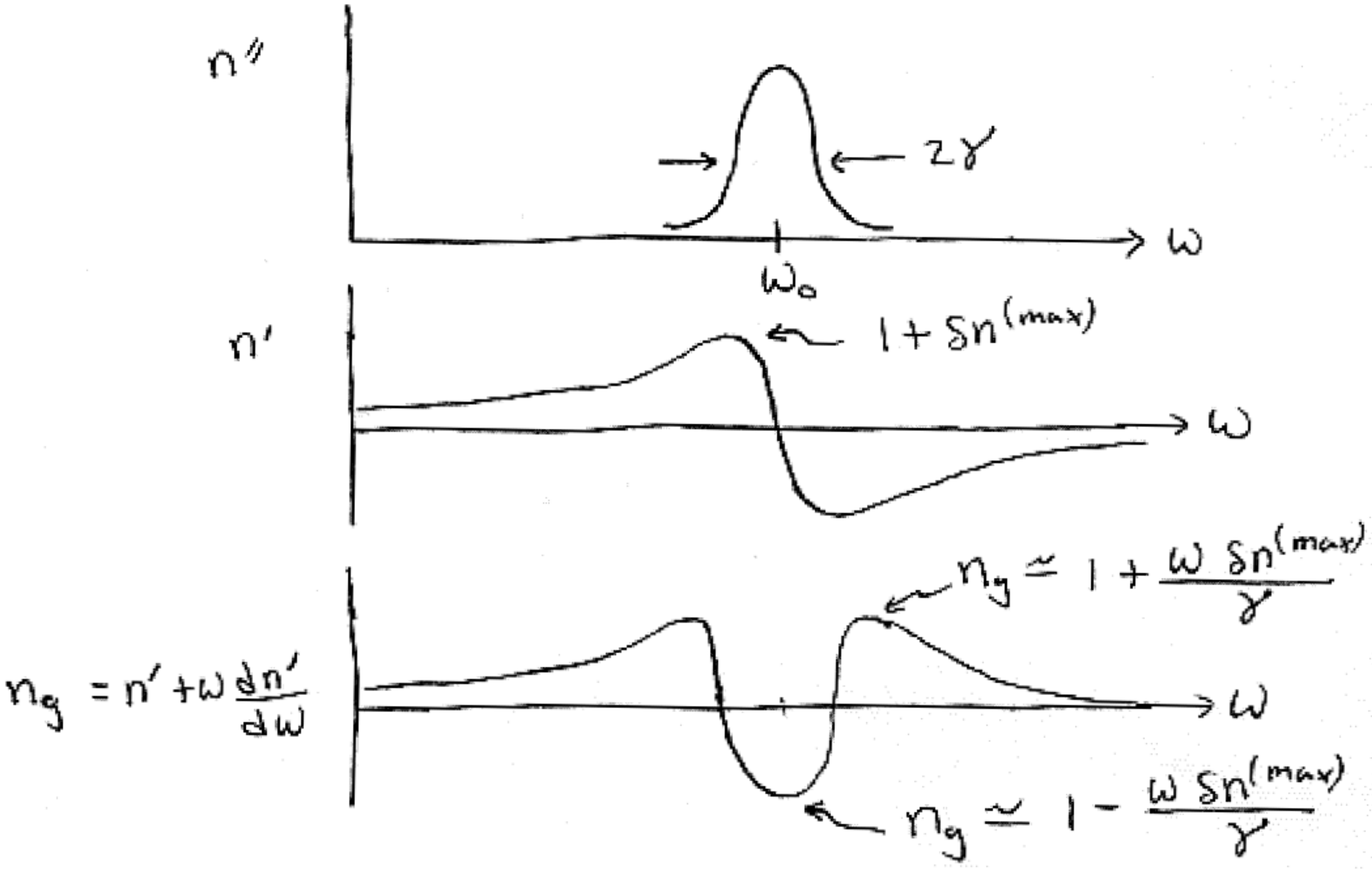
Light Propagation in Atomic Vapors

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

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

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

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



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

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 . . .

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

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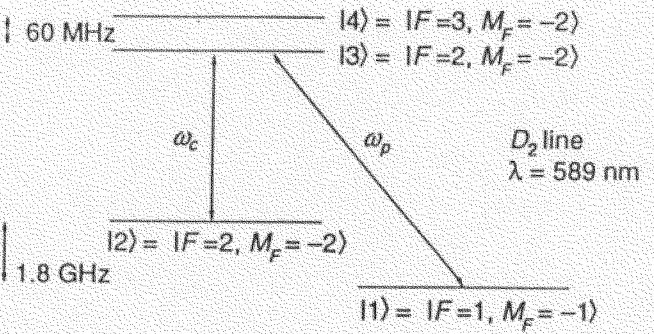
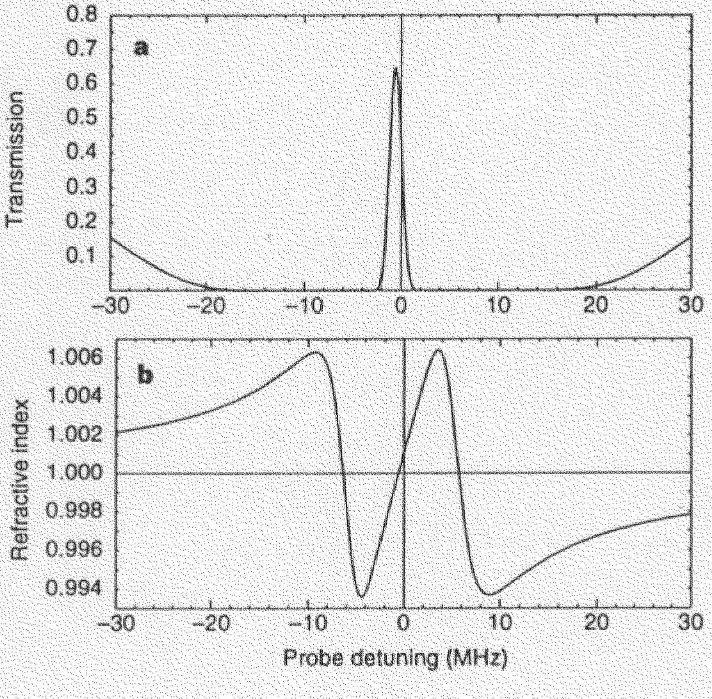
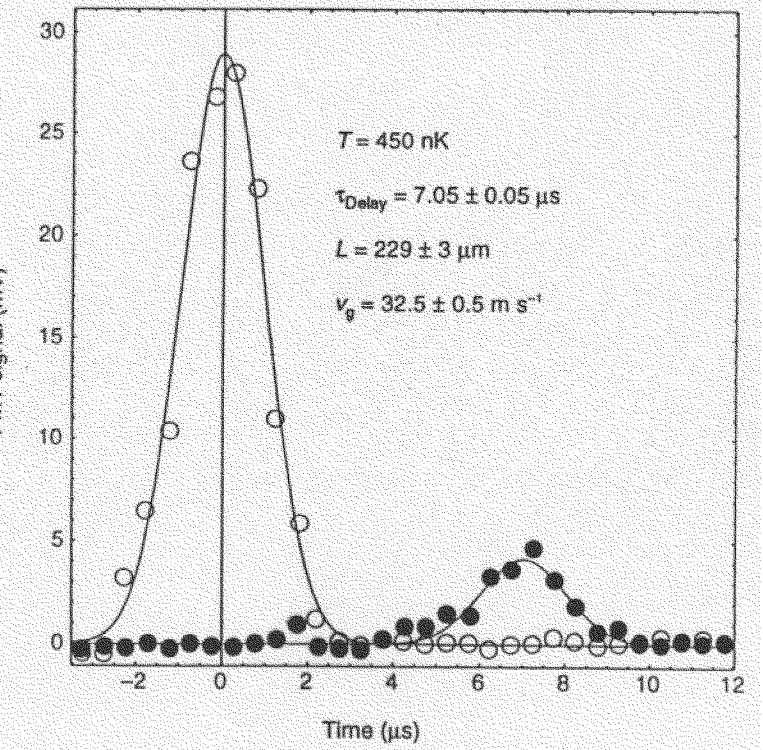
‡ *Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

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 cohernt population oscillations (a quantum coherence effect that is relatively insensitive to dephasing processes).

Slow Light in Ruby

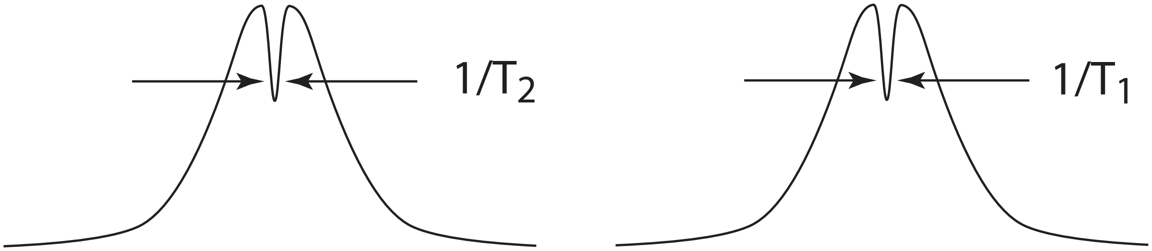
Need a large dn/dω. (How?)

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 $T_2 << T_1$.

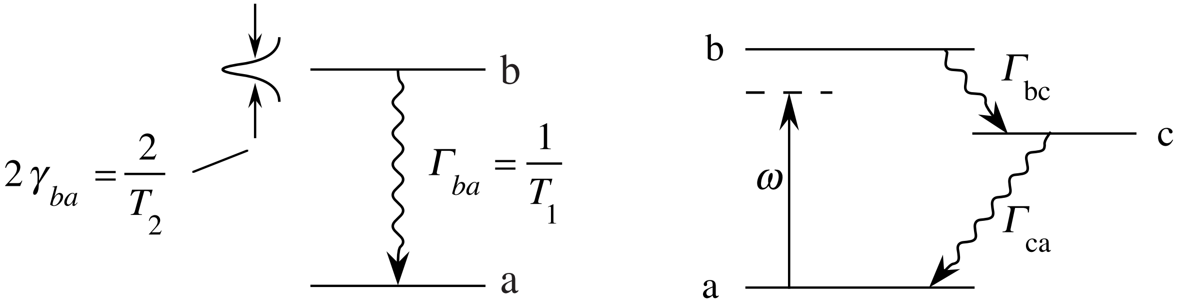


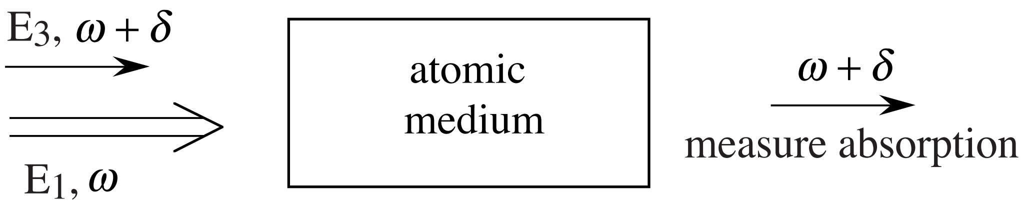
inhomogeneously broadened medium

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 $\delta \le 1/T_1$

Probe-beam response:

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

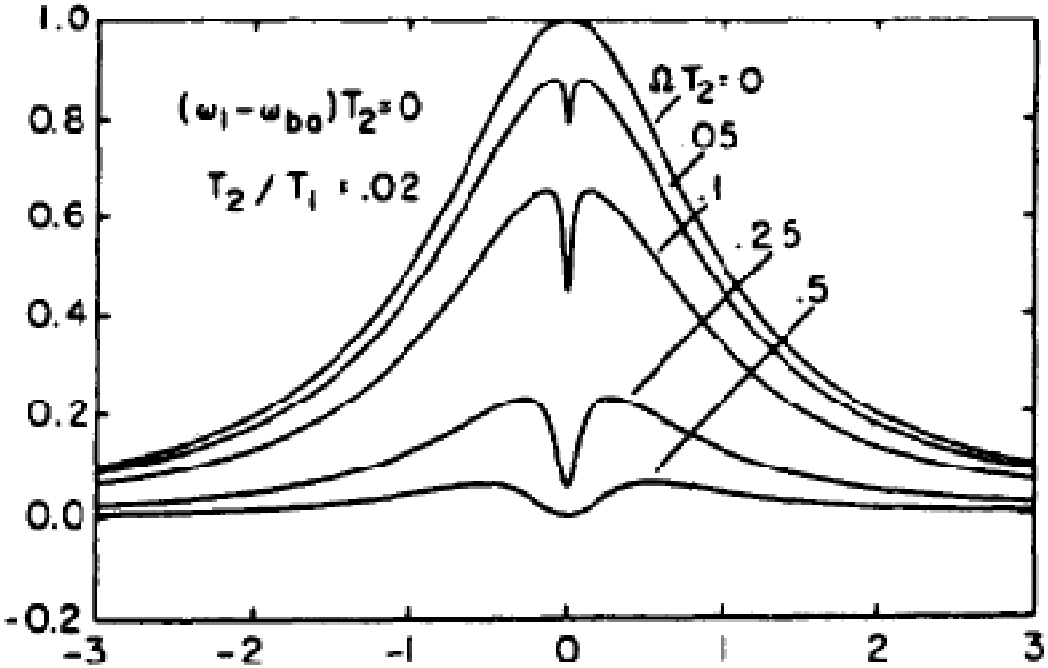
Probe-beam absorption:

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

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

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.

Volume 45, number 6 OPTICS COMMUNICATIONS 15 May 1983

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

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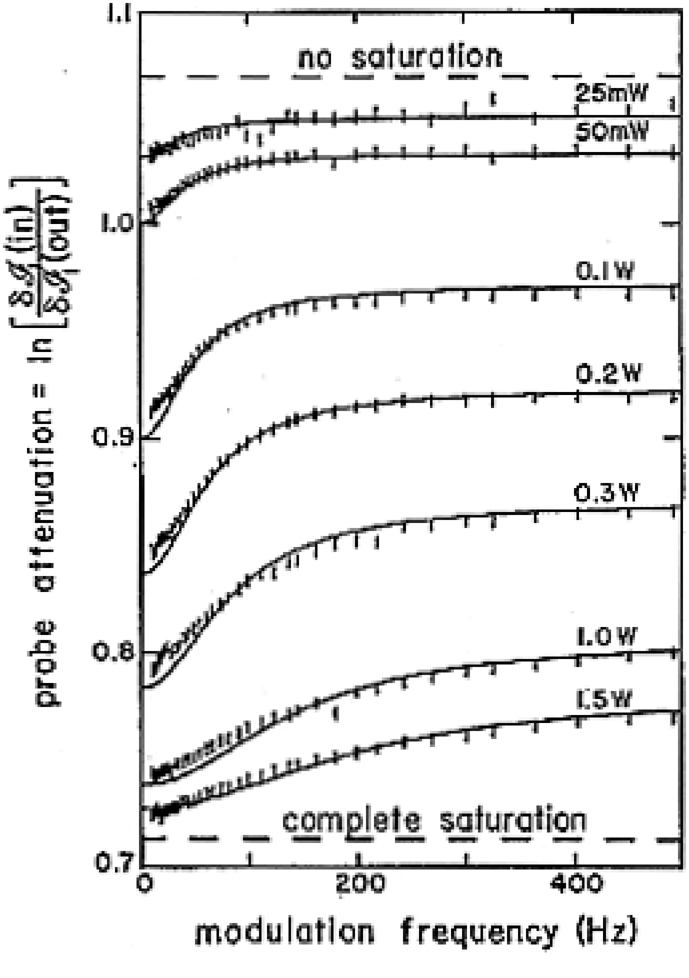
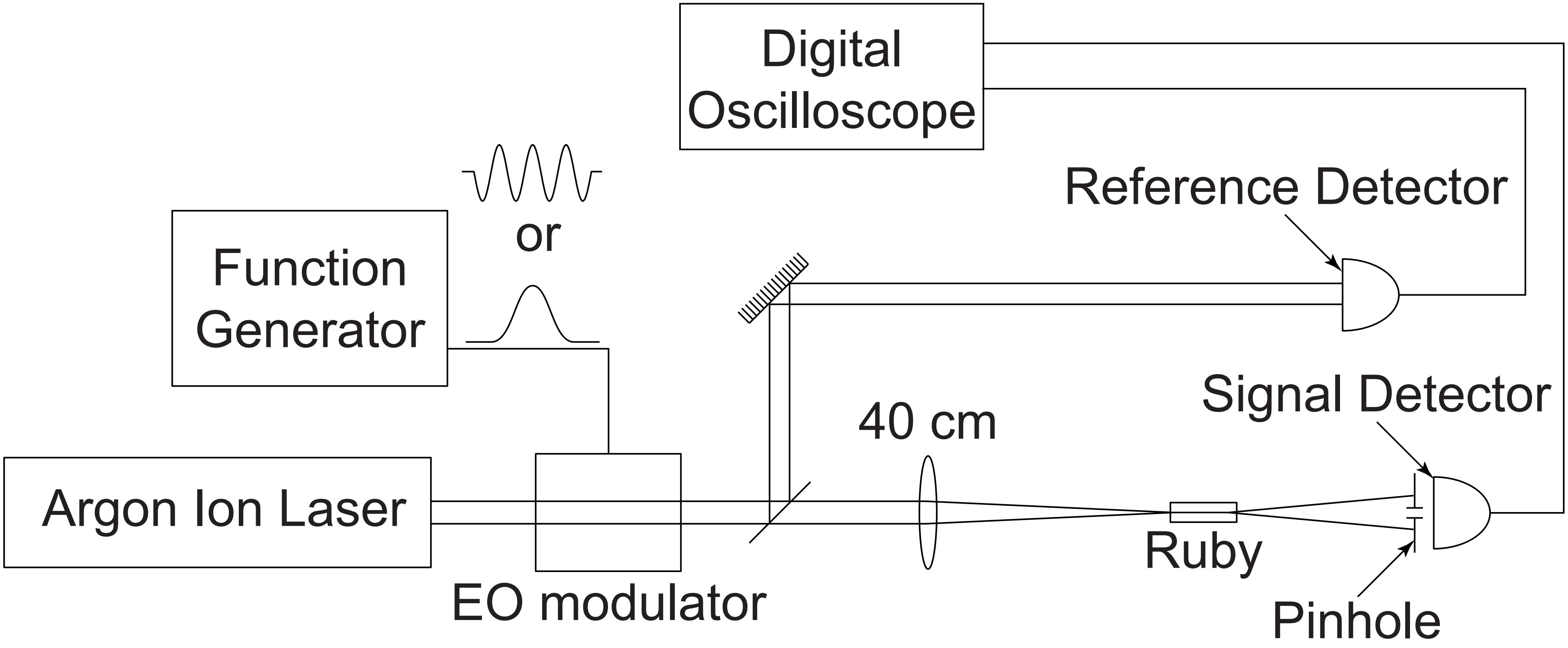
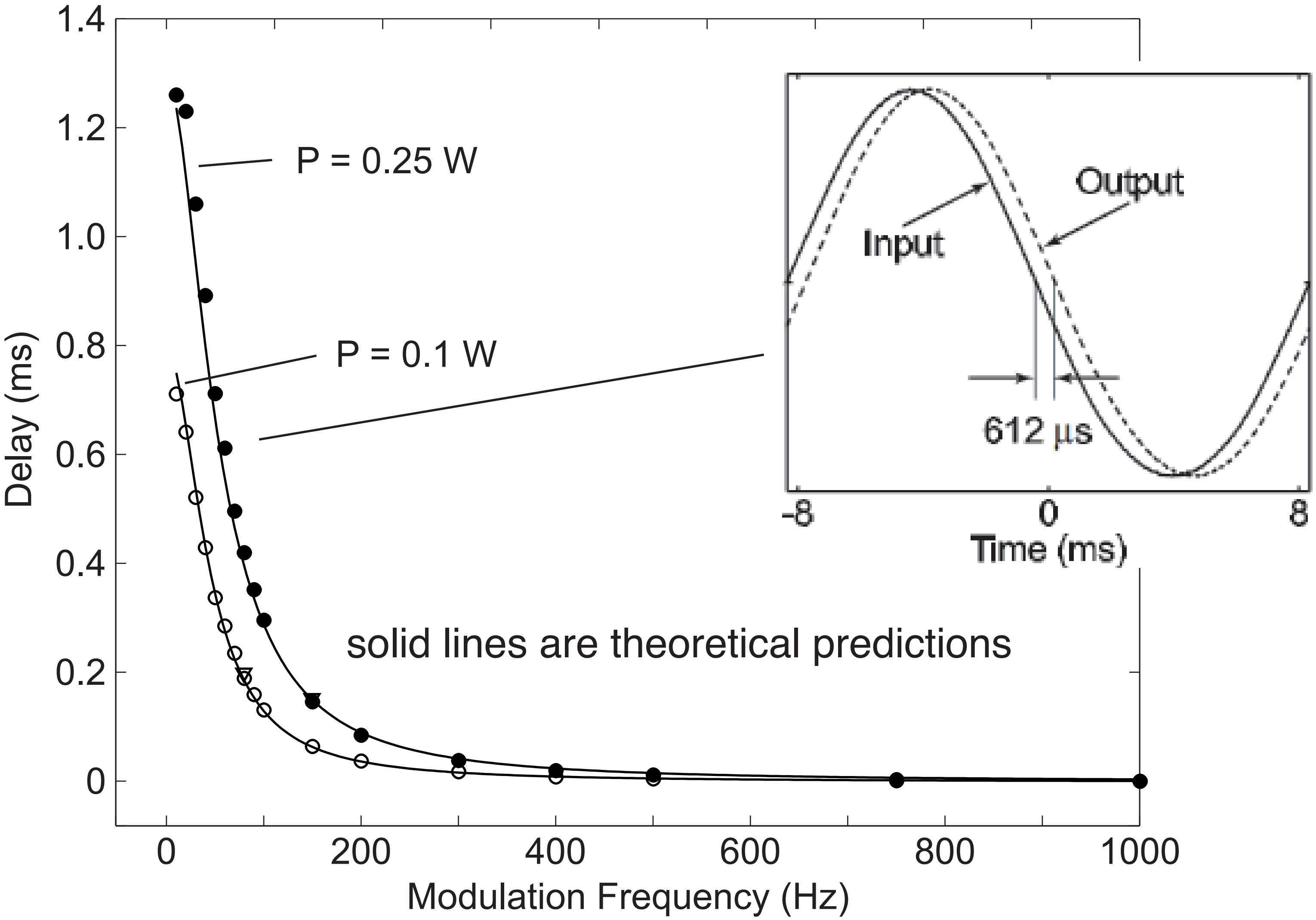


Slow Light Experimental Setup



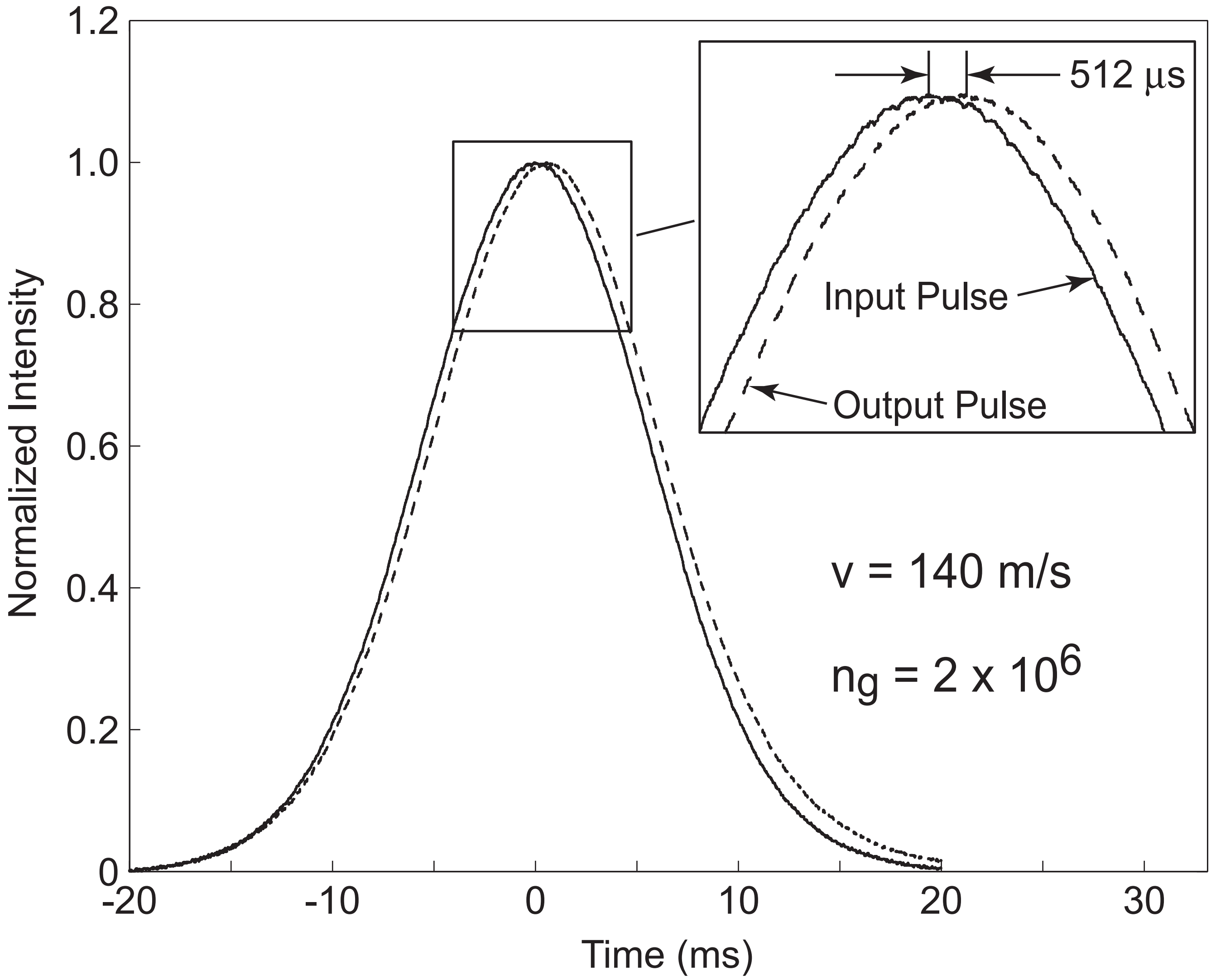
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



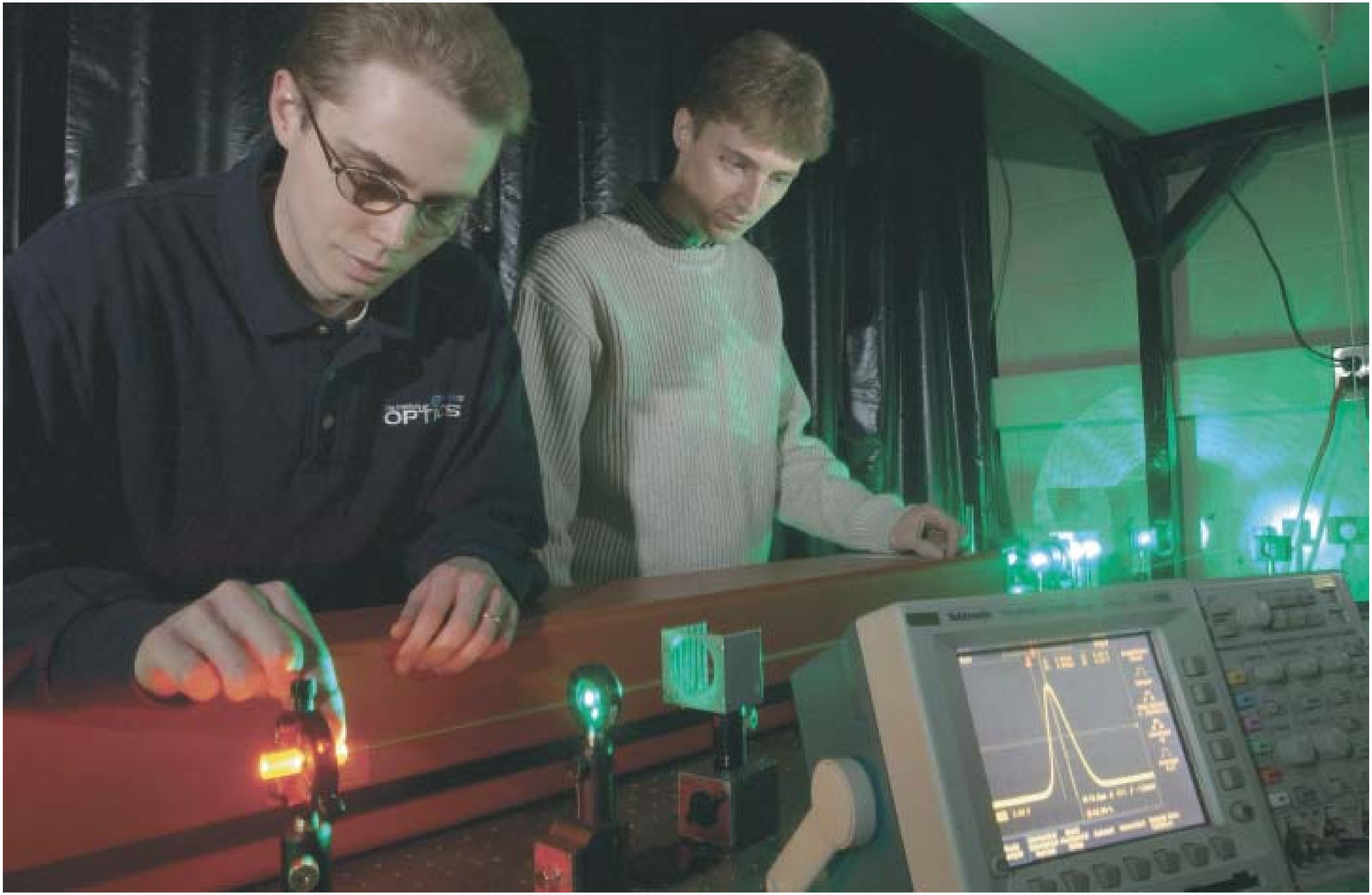
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

Gaussian Pulse Propagation Through Ruby

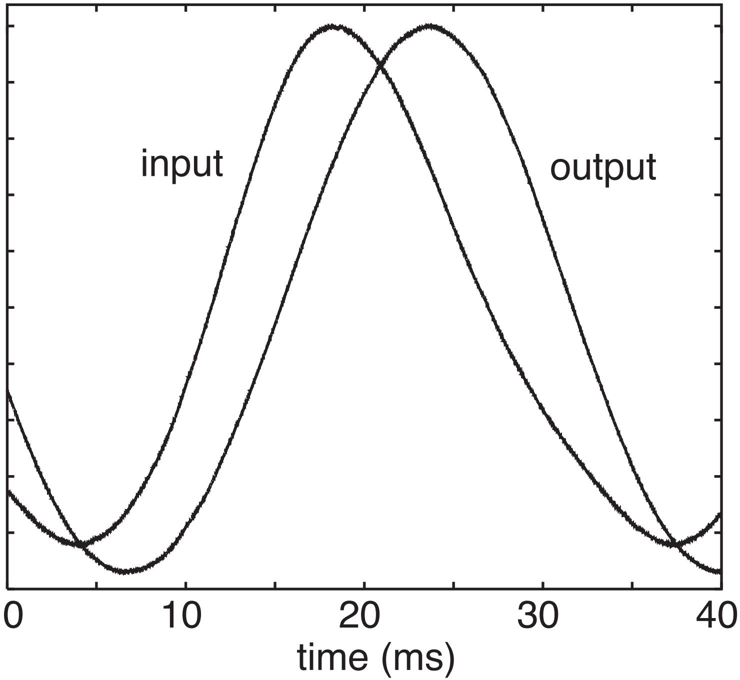


No pulse distortion!

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

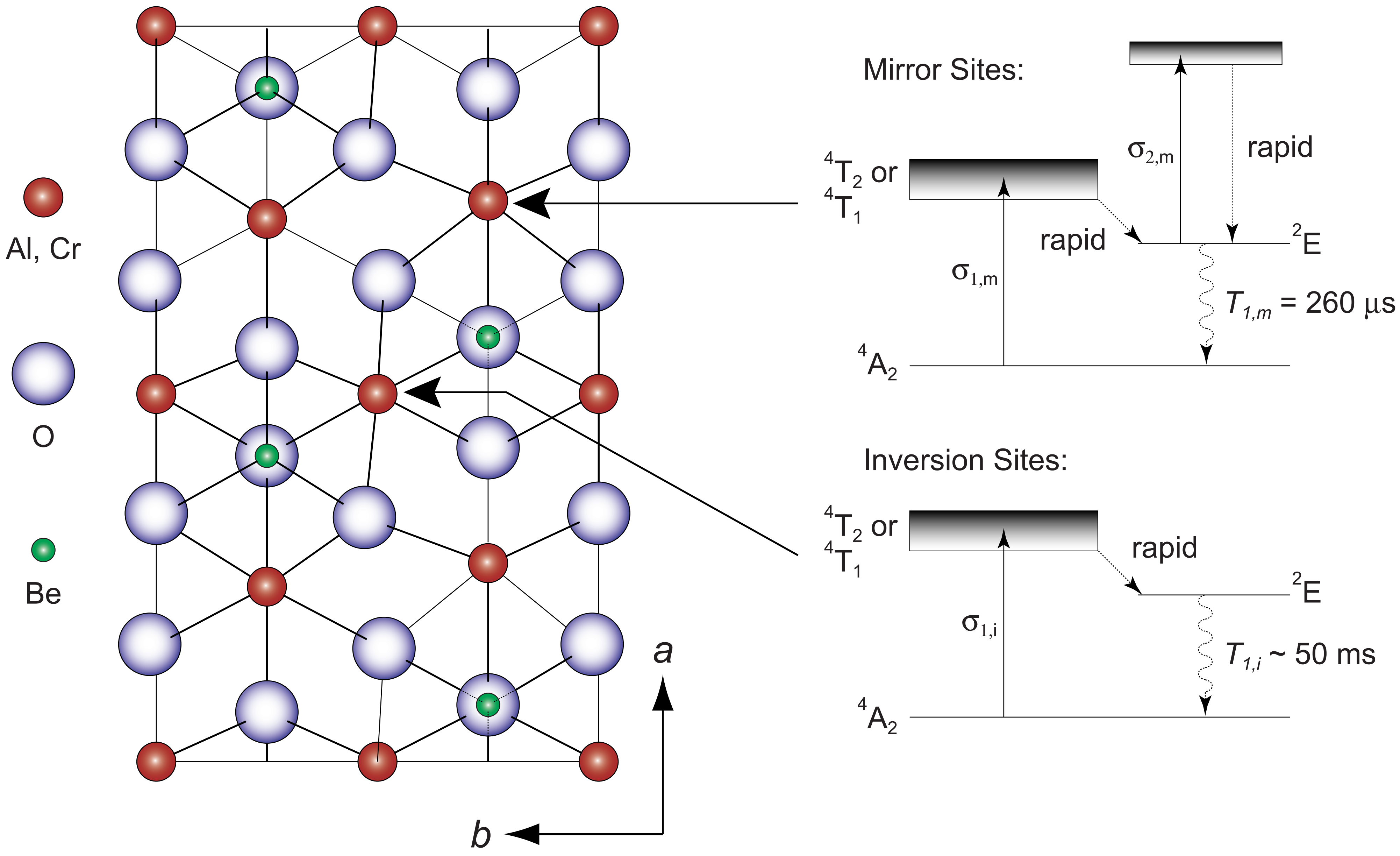
Insensitive of dephasing processes

Laser need not be frequency stabilized

Works with single beam (self-delayed)

Delay can be controlled through input intensity

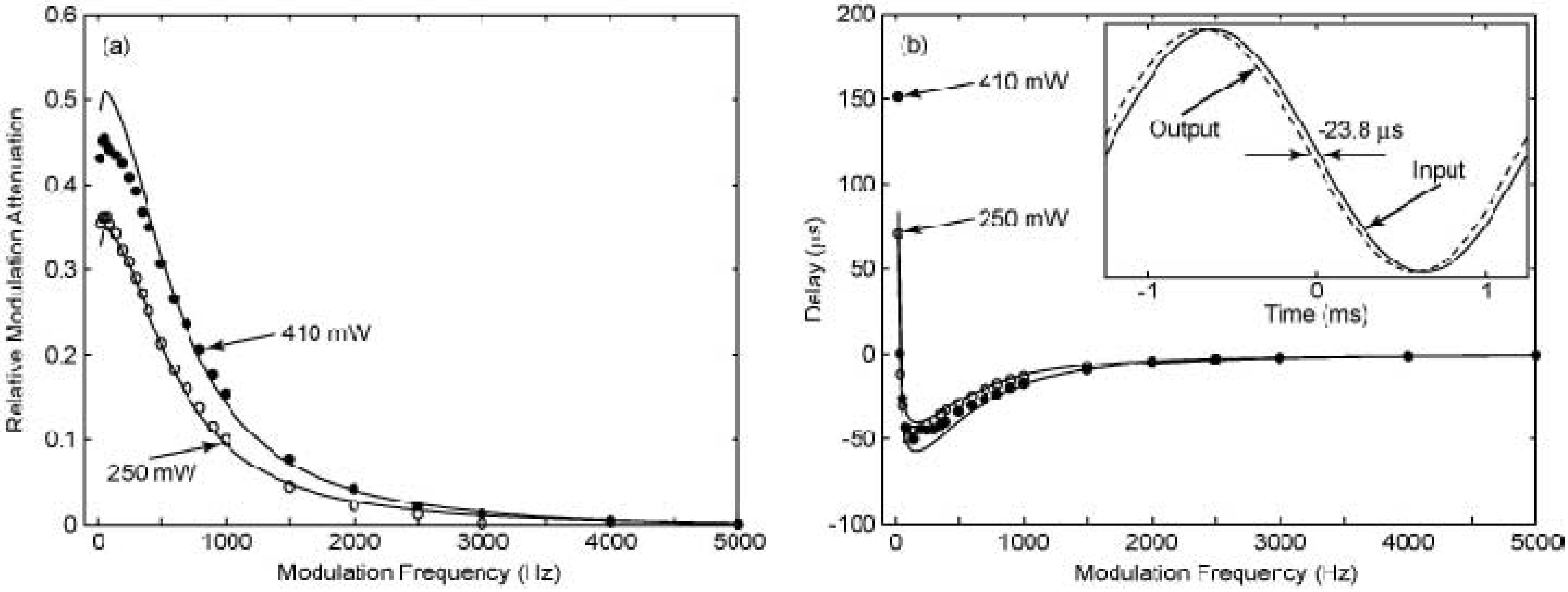
Alexandrite Displays both Saturable and Inverse-Saturable Absorption



Inverse-Saturable Absorption Produces Superluminal Propagation in Alexandrite

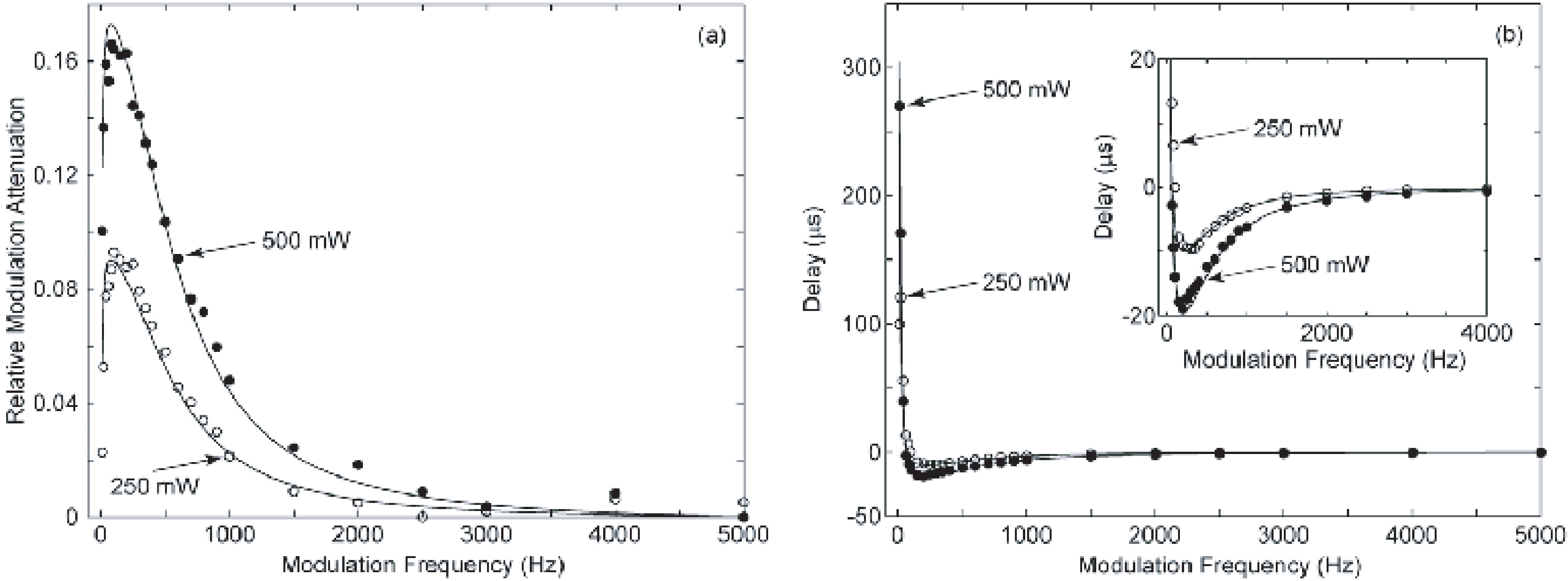
At 476 nm, alexandrite is an inverse saturable absorber

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



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

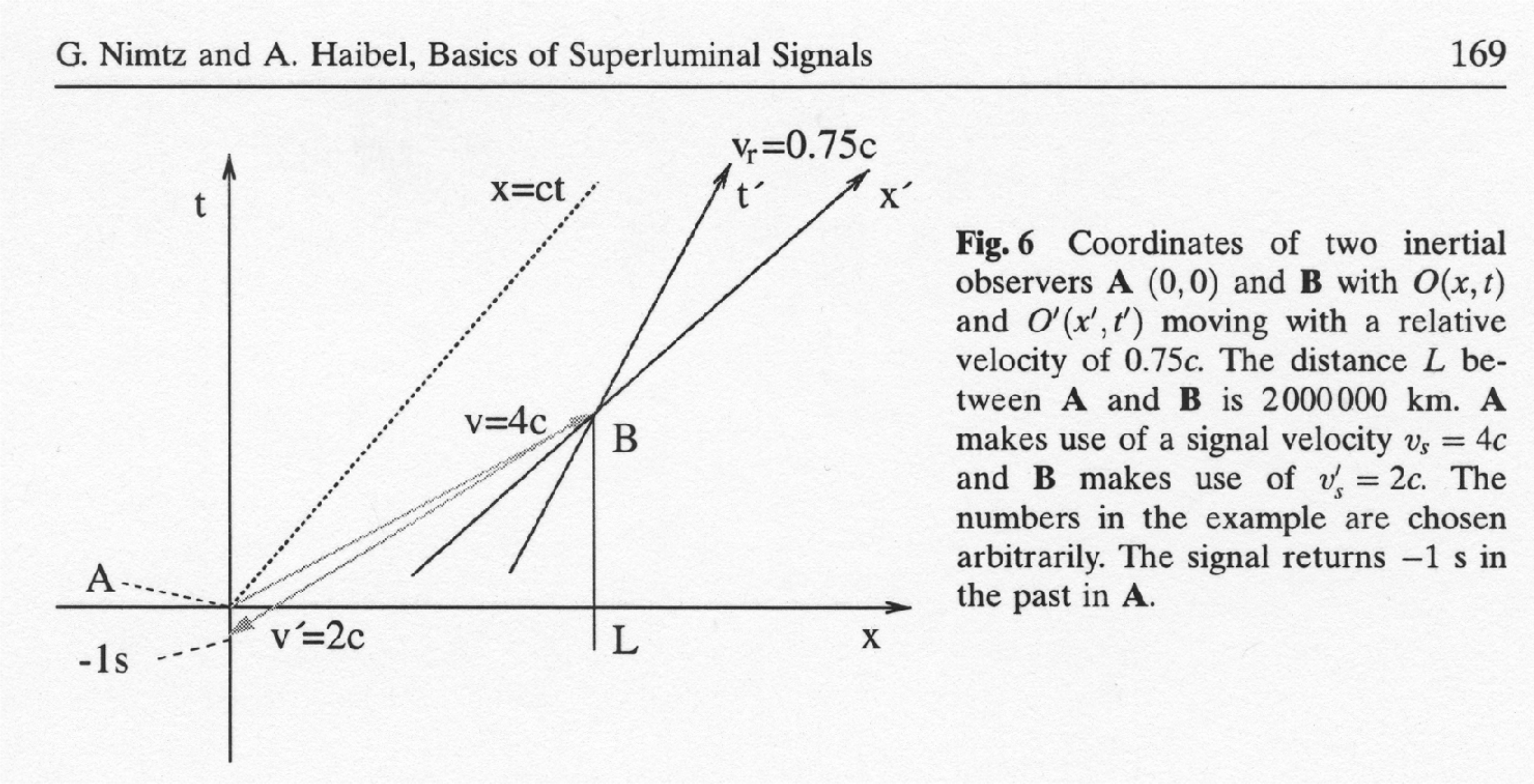
Probe Absorption and Delay at 488 nm



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

□ □ □ Science 301 , 200 (2003).

Causality and Superluminality

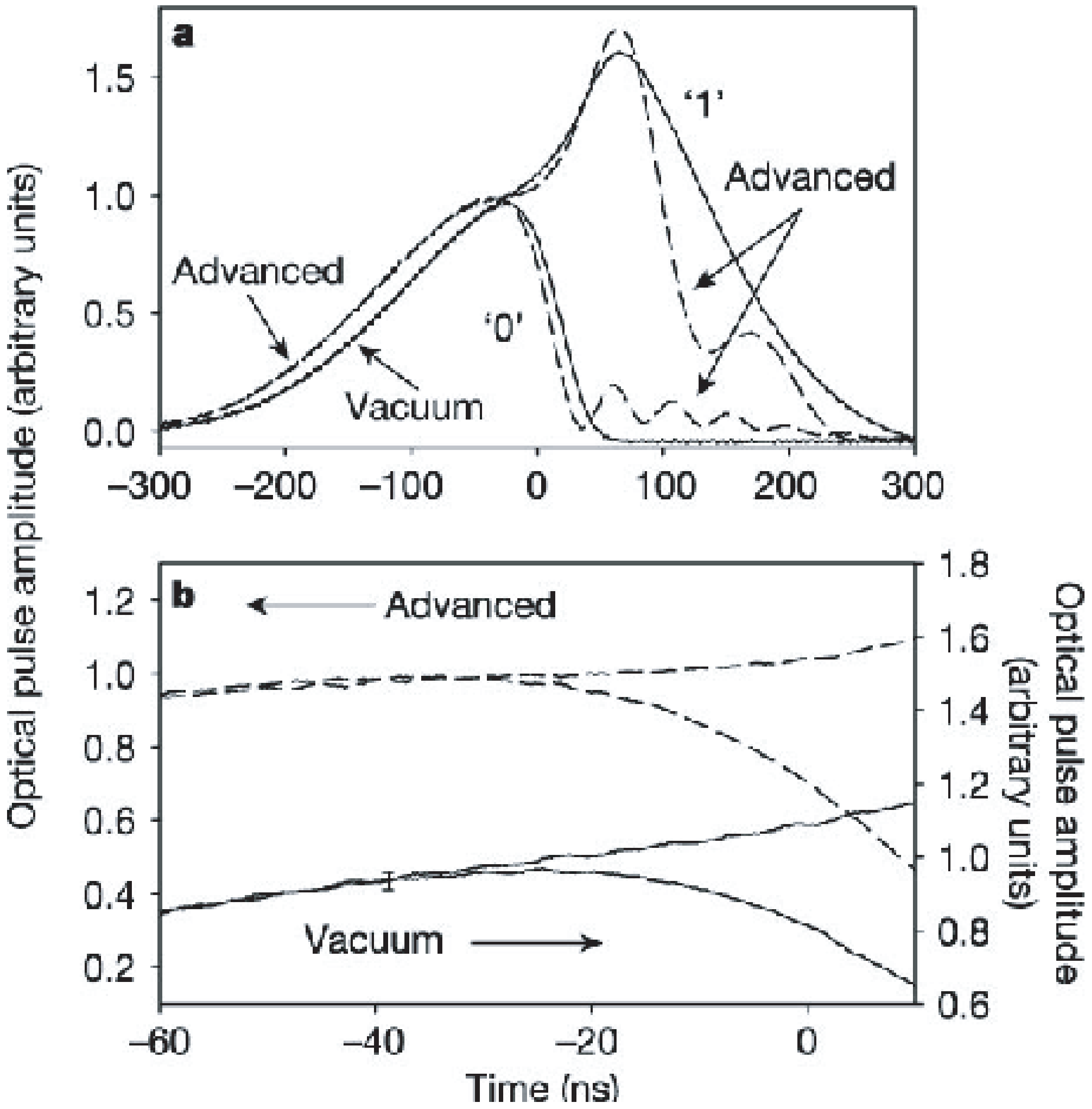


G. Nimtz and A. Haibel, Basics of Superluminal Signals 169

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 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.

Information Velocity in a Fast Light Medium

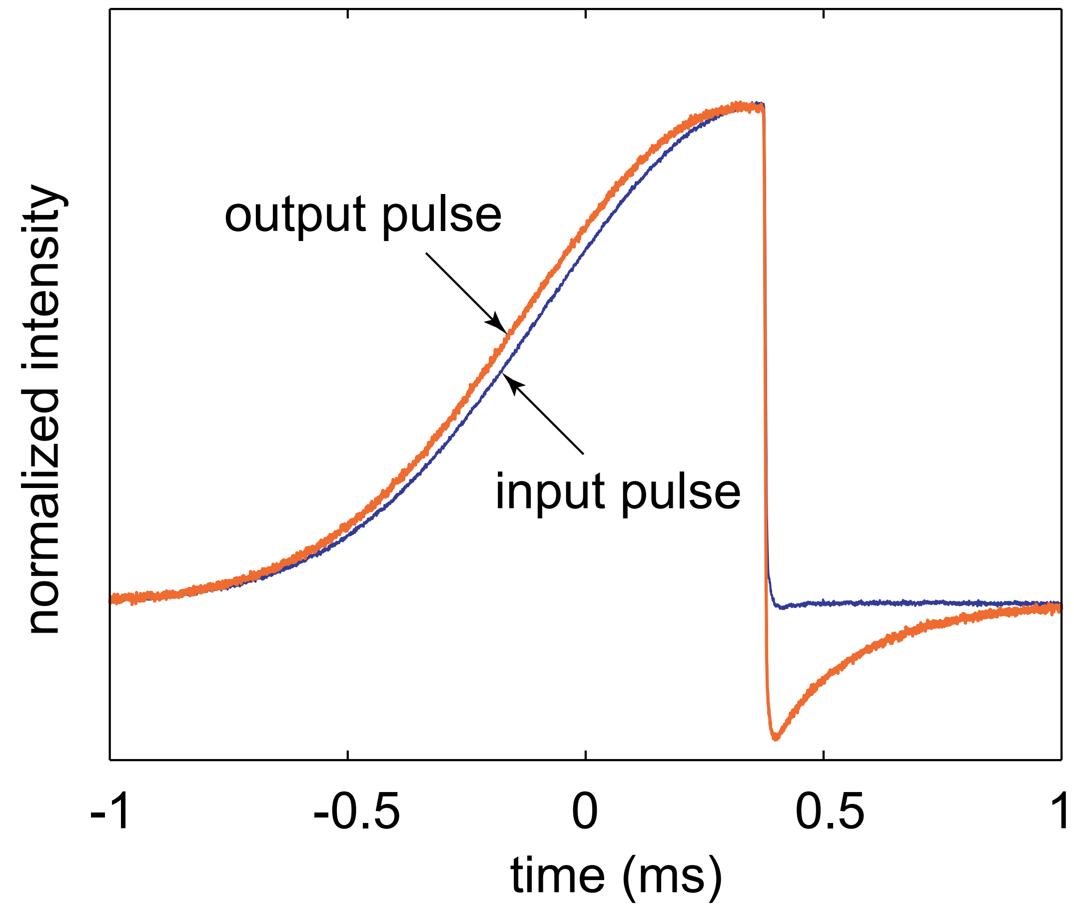


M.D. Stenner, D.J. Gauthier, and M.I. Neifeld, Nature,425 695 (2003).

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

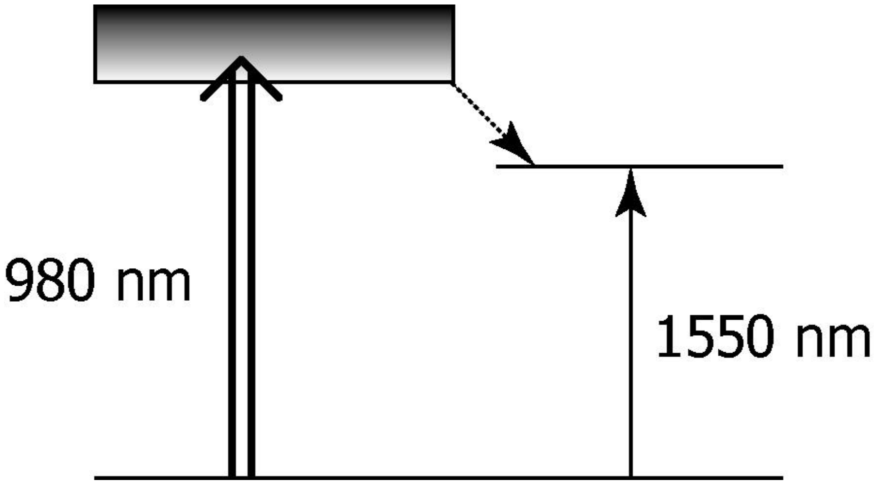
Slow and Fast Light --What Next?

Longer fractional delay
    (saturate deeper; propagate farther)

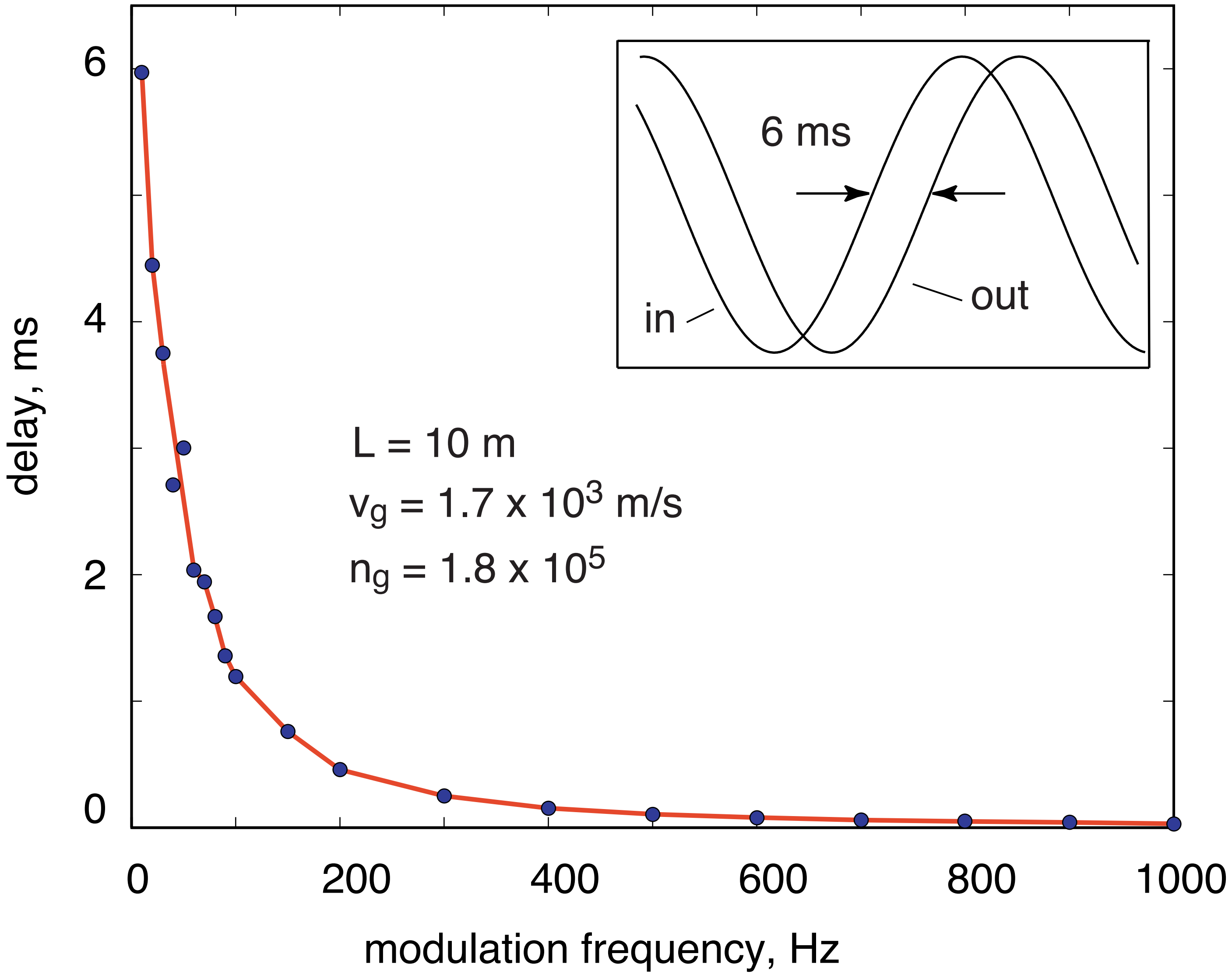
Find material with faster response
    (technique works with shorter pulses)

Slow and Fast Light in a Er-doped Fiber Amplifier

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



Slow Light in an Erbium-Doped Fiber Amplifier



L = 10 m

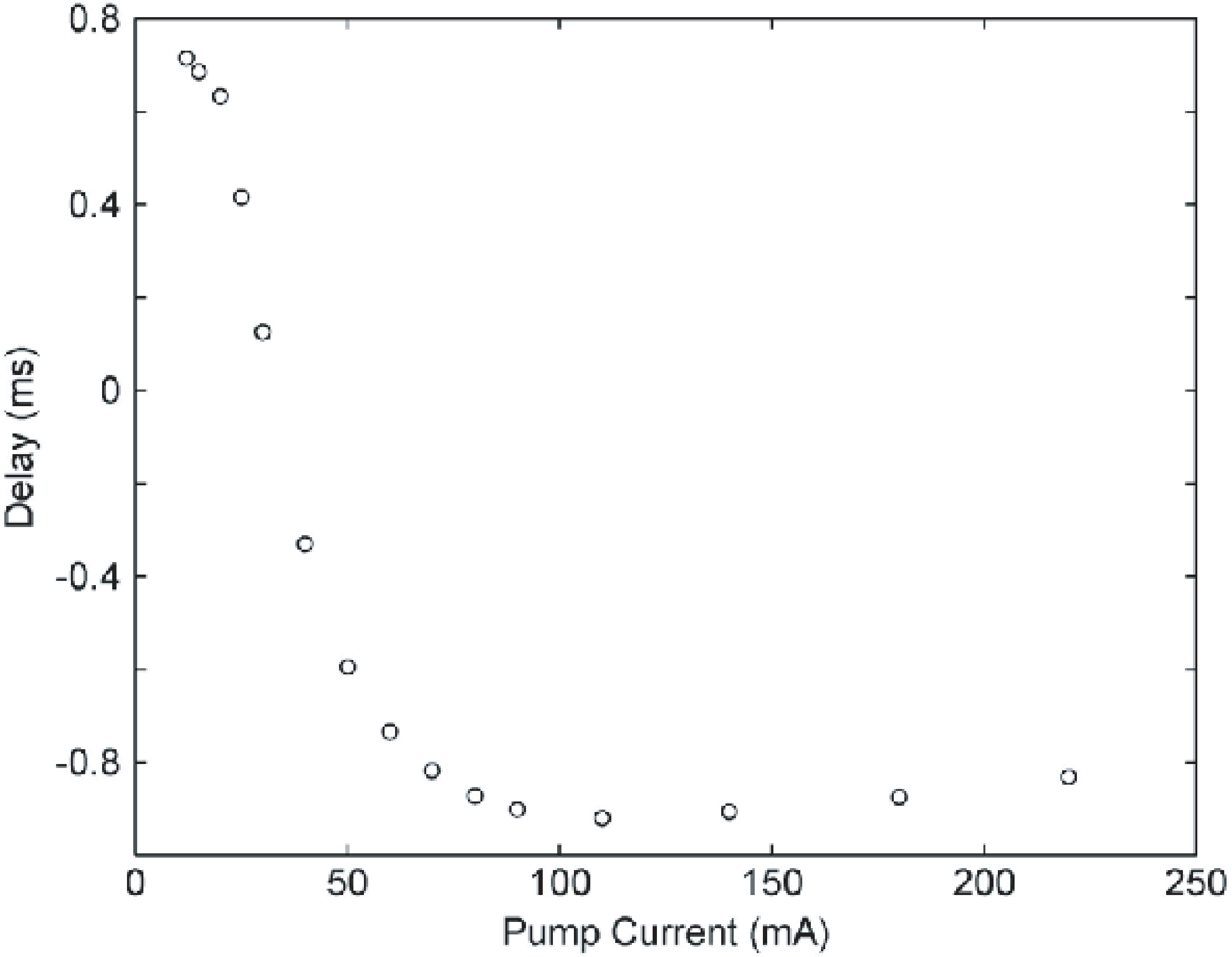
$v_g = 1.7 \times 10^3$ m/s

$n_g = 1.8 \times 10^5$

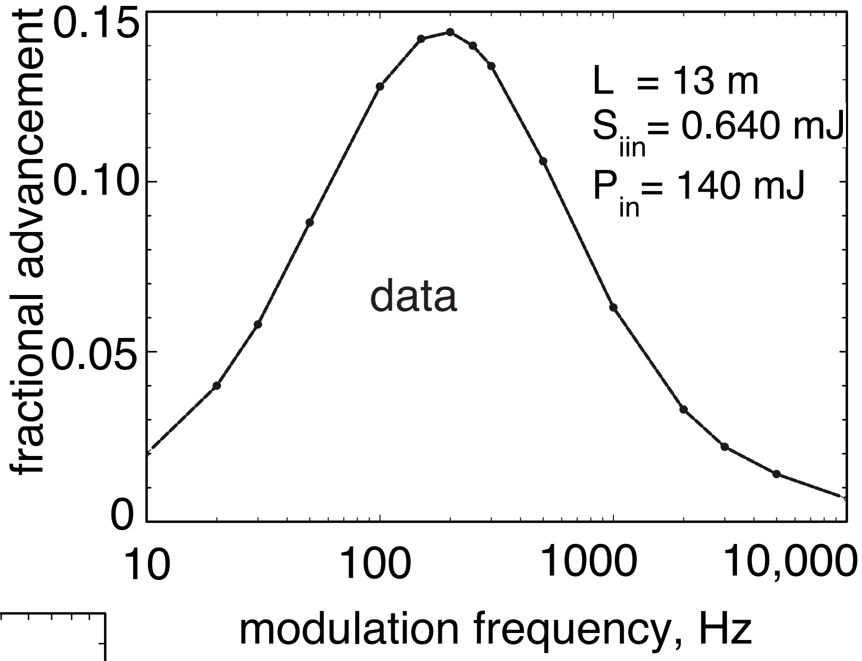
after S. Jarabo, University of Zaragoza

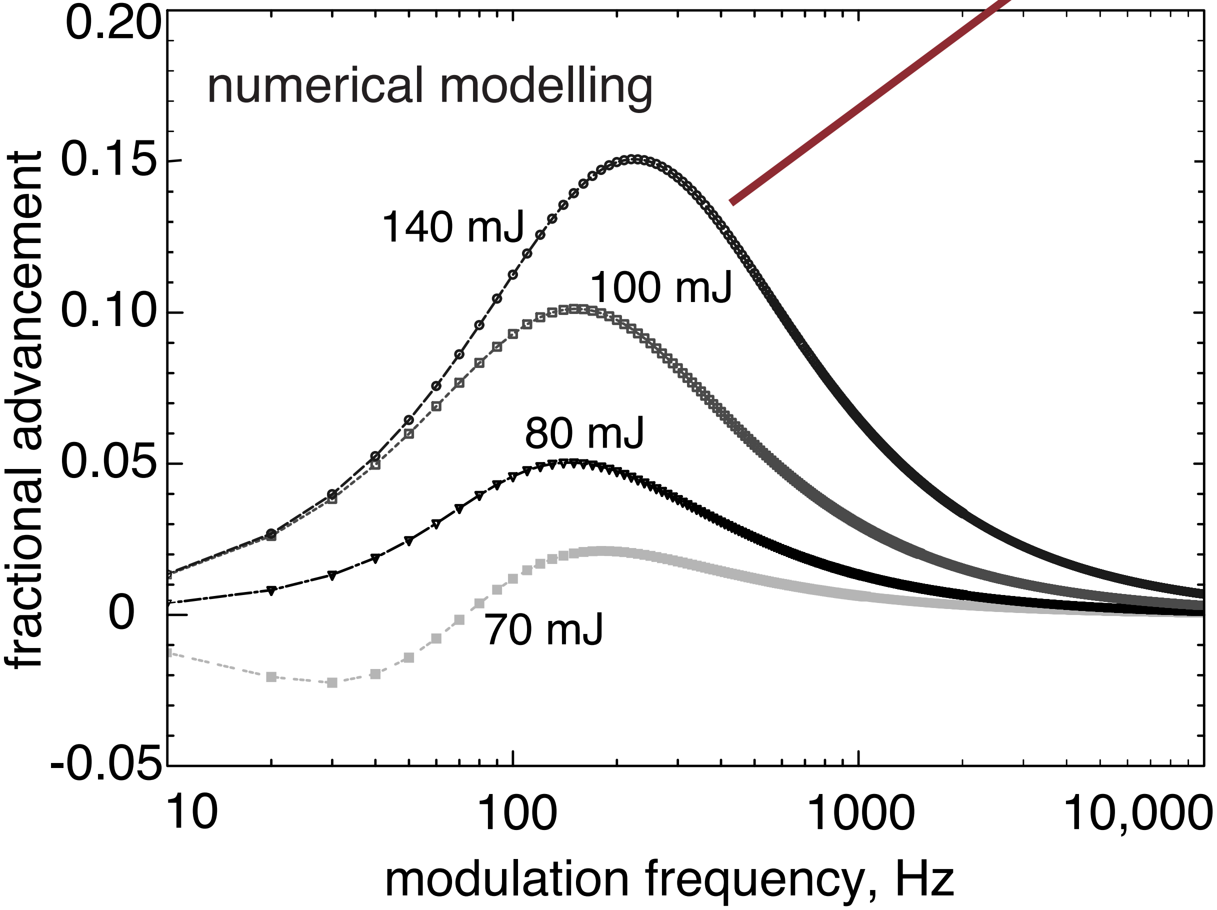
Pump Power Dependence of Time Delay

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



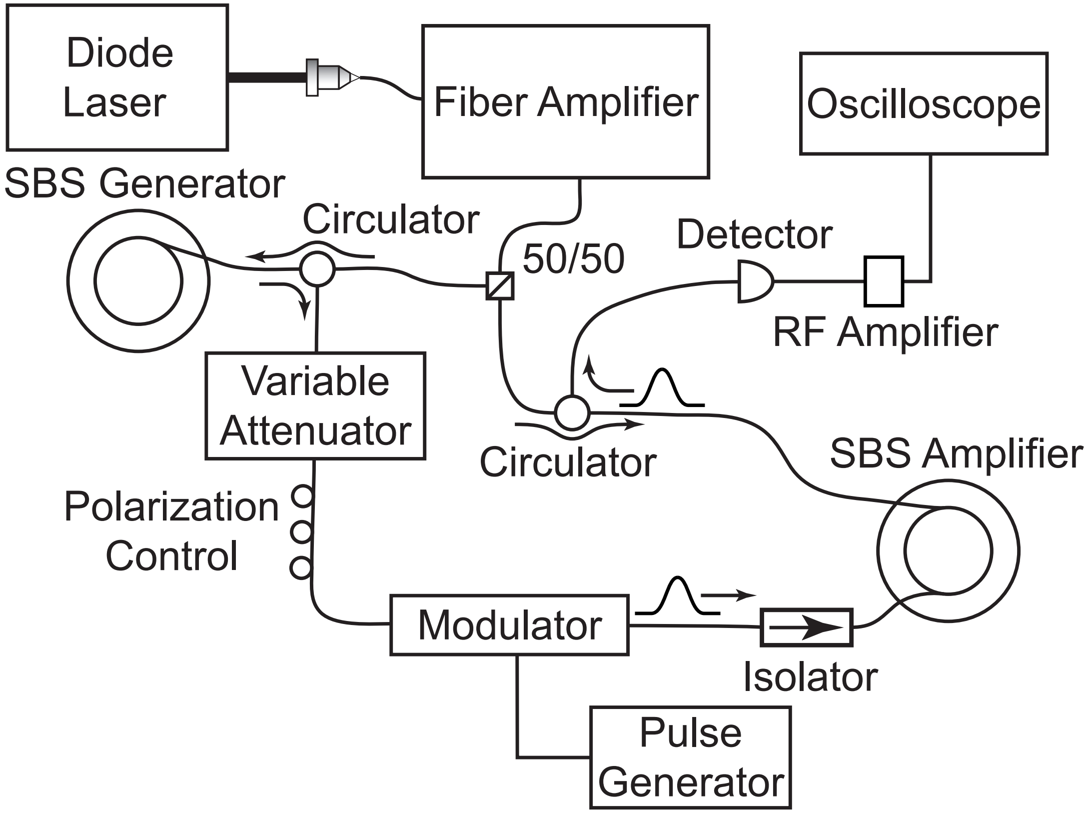
Modelling Slow and Fast Light in Erbium



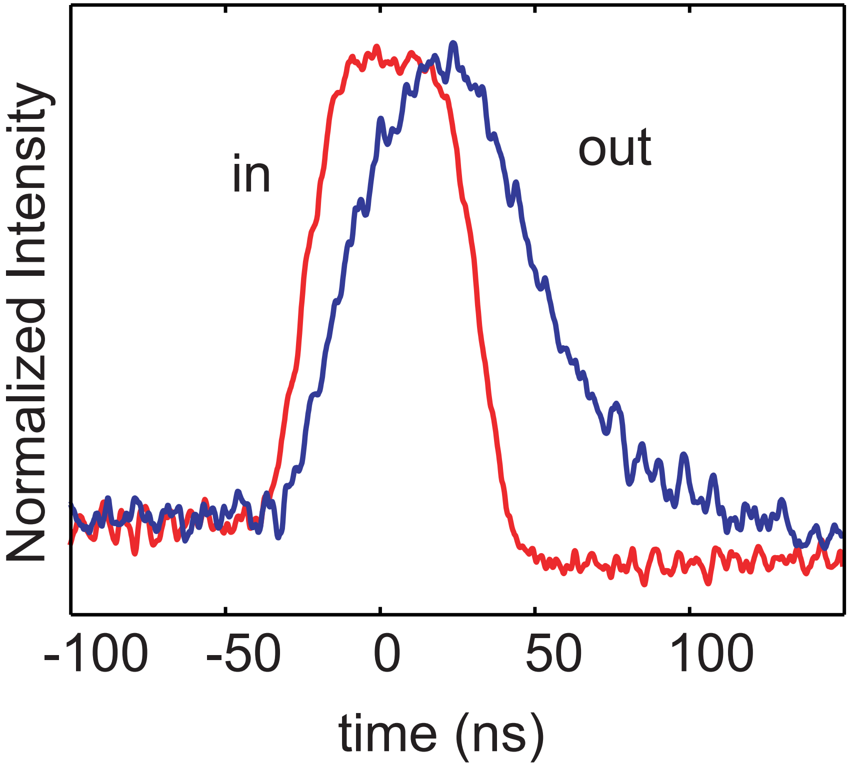


Slow-Light via Stimulated Brillouin Scattering

- 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



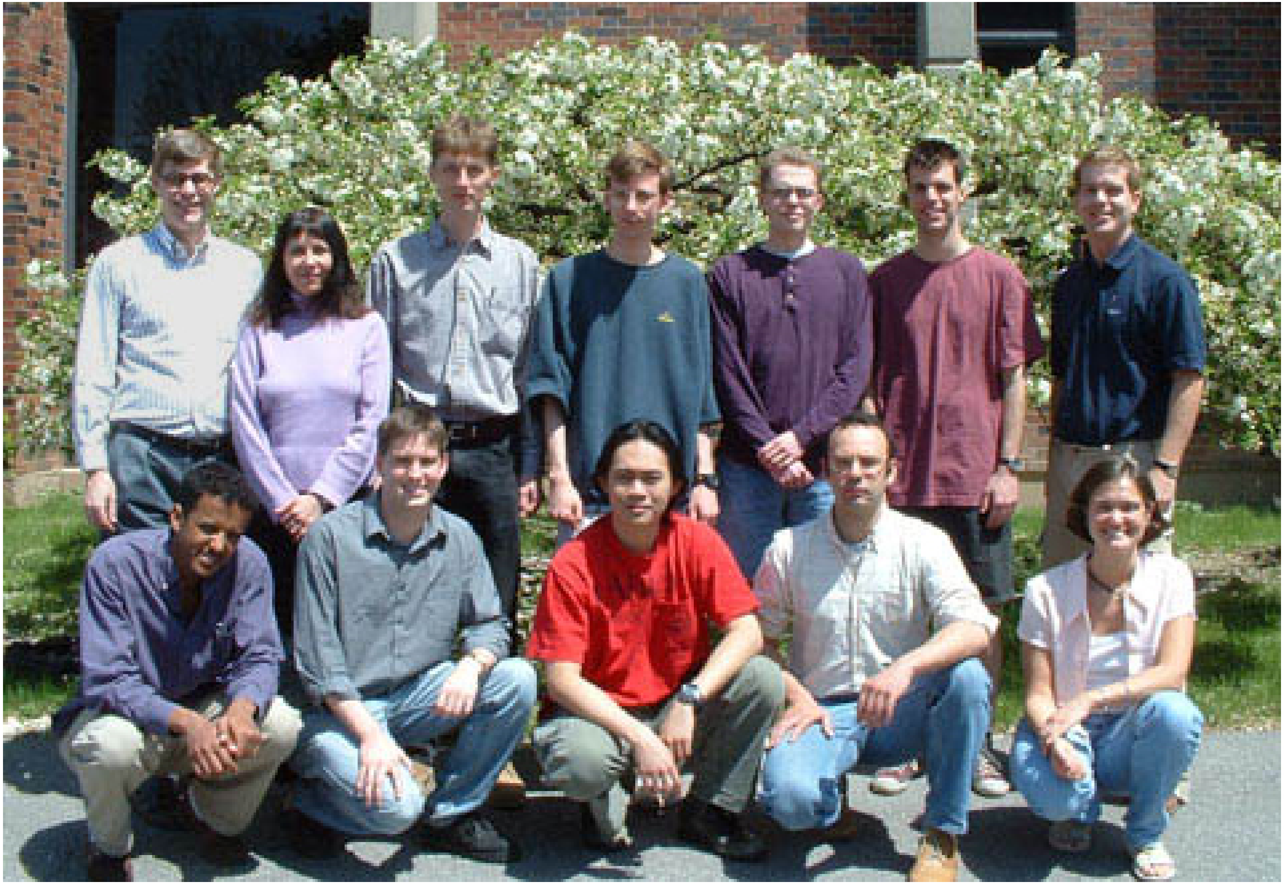
early data



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 NSF for financial support!