Slow and Fast Light in Room-Temperature Solids: Fundamental and Applications

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Interest in Slow Light

Intrigue: Can (group) refractive index really be 10^6?

Fundamentals of optical physics

Optical delay lines, optical storage, optical memories

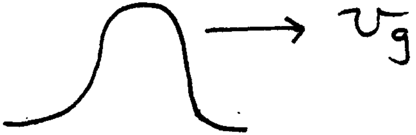
Implications for quantum information

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

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

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!

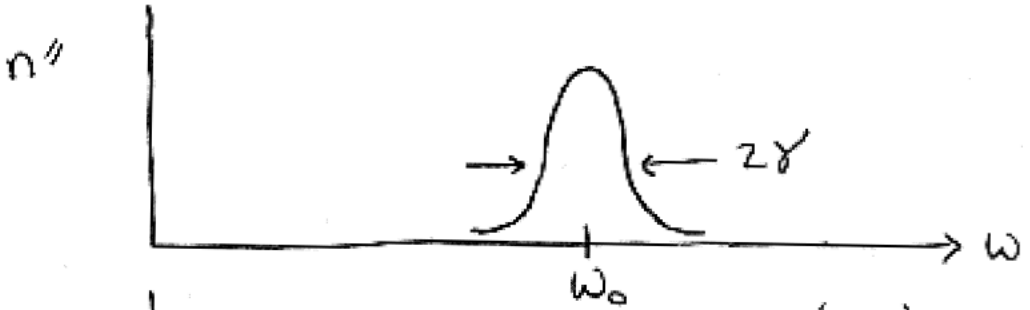
Light Propagation in Atomic Vapors

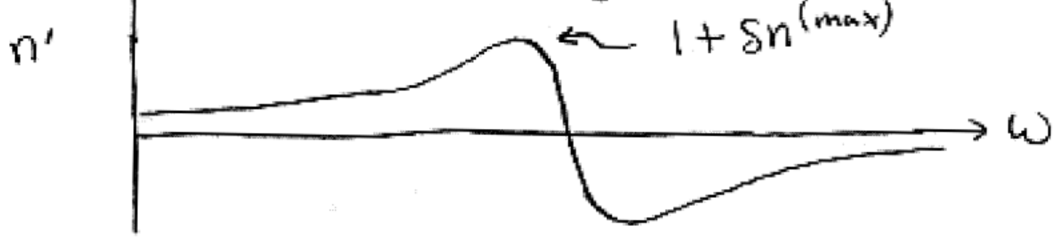
$$n = \sqrt{\epsilon} = \sqrt{1+4\pi\chi} \qquad \chi = \frac{Ne^2/2m\omega_0}{(\omega_0-\omega)-i\gamma}$$

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

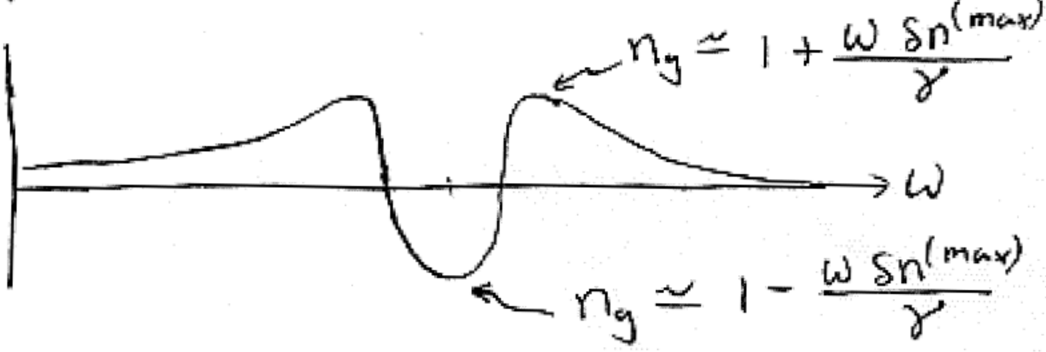
$$n' \simeq 1 + \frac{\pi N e^2}{m\omega_0}\,\frac{\omega_0-\omega}{(\omega_0-\omega)^2+\gamma^2}$$

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





$n_g = n' + \omega \dfrac{dn'}{d\omega}$



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

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)

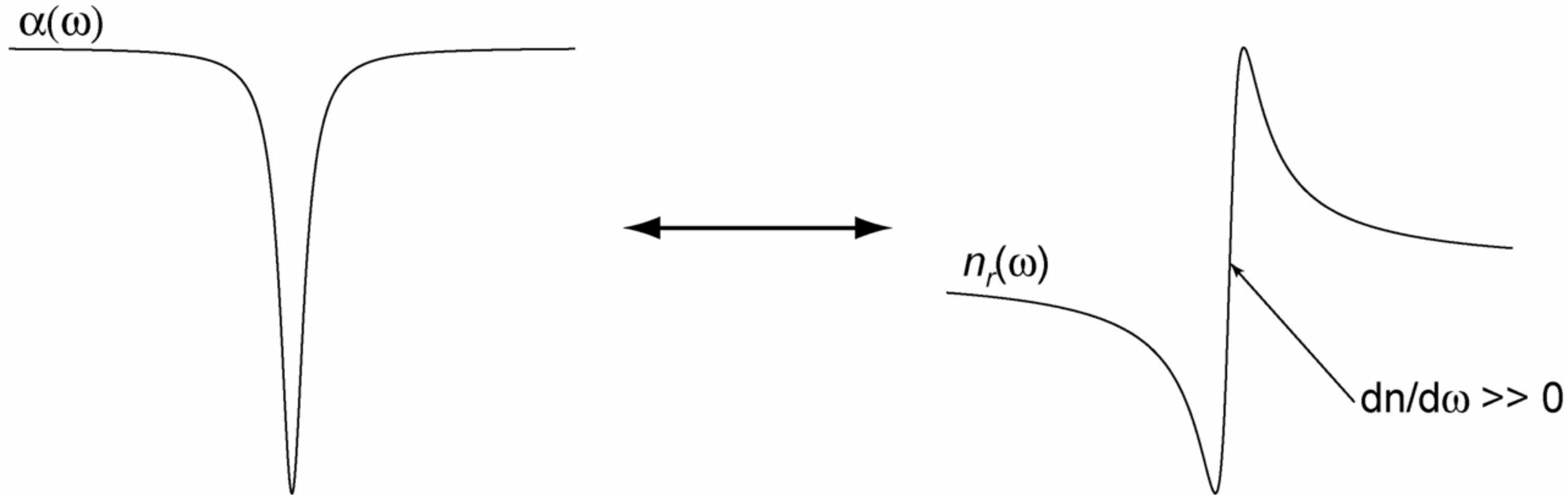
(2) decrease absorption

(so transmitted pulse is detectable)

Kramers-Kronig Relation

- Group index: $n_g = n_0 + \omega \dfrac{dn}{d\omega}$

$$\alpha(\omega) = -\frac{2\omega^2}{\pi c} P \int_0^\infty \frac{n_r(s)}{s^2 - \omega^2} ds \longleftrightarrow n_r(\omega) = 1 + \frac{2c}{\pi} P \int_0^\infty \frac{\alpha(s)}{s^2 - \omega^2} ds$$



- Want a very narrow dip in the absorption.

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

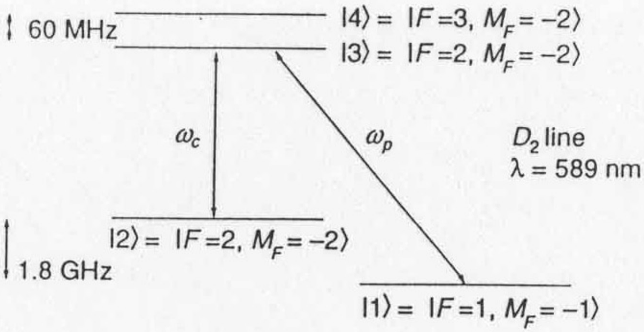
Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§

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

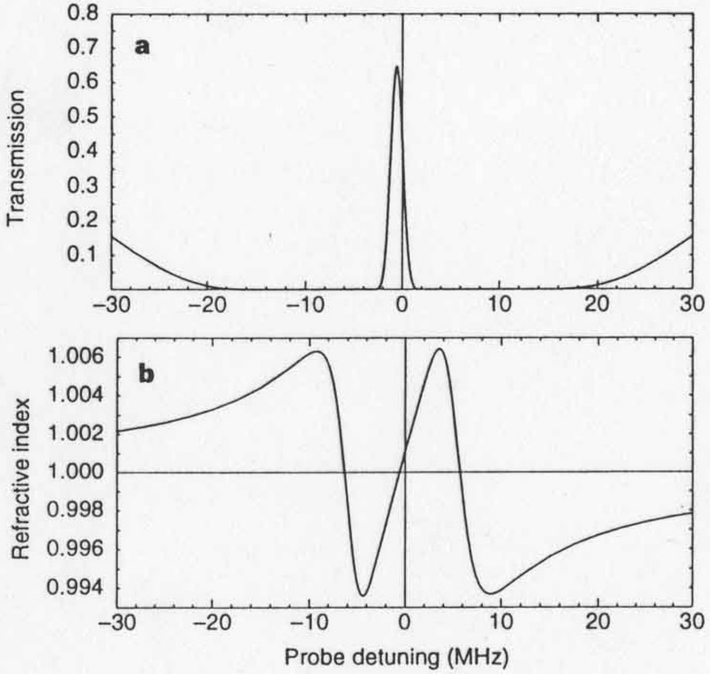
† *Department of Physics, § Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*

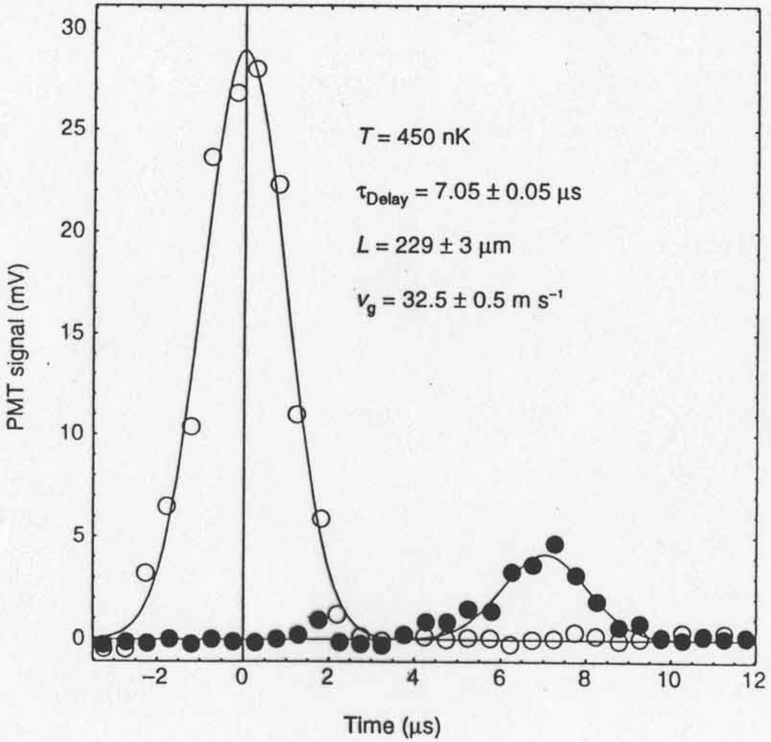
‡ *Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

Nature 397, 594 1999



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





Review of Ultra-Slow Light

- Resonant System:

  Absorber ($\alpha_0 \sim 10^5\ \mathrm{cm}^{-1}$) S. Chu and S. Wong, Phys. Rev. Lett. **48**, 738 (1982).

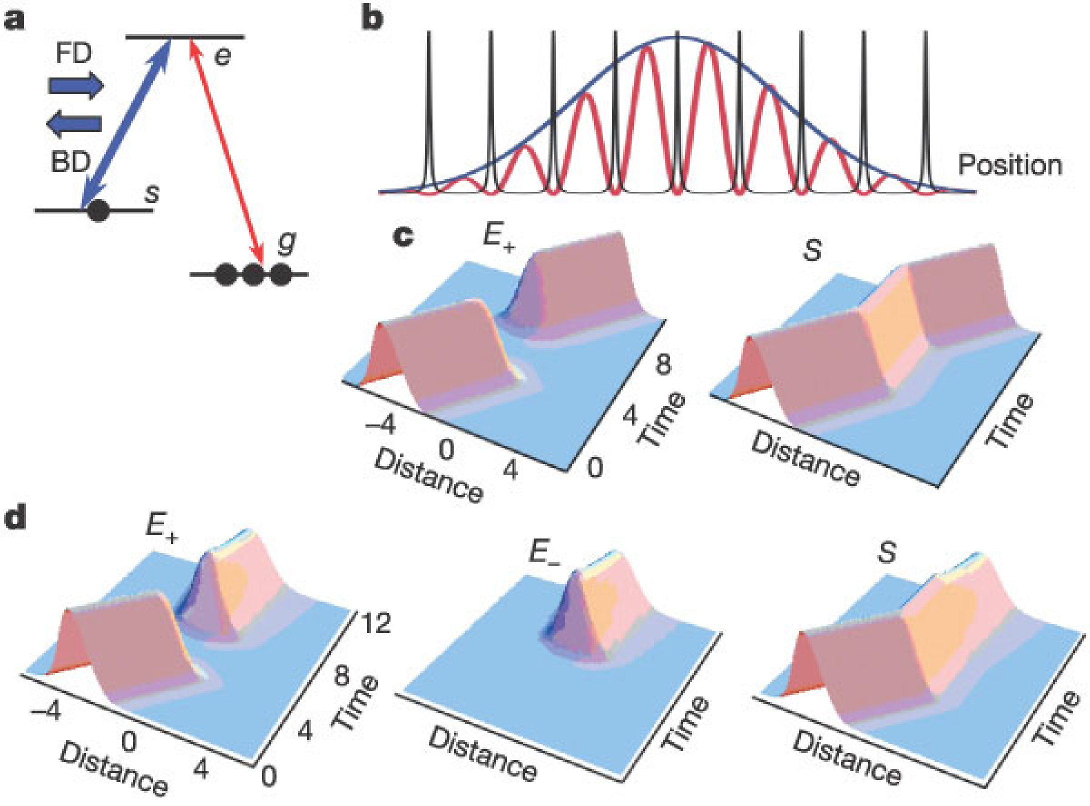
- EIT

  17 m/s in a BEC L. Hau *et al.*, Nature, **397**, 594 (1999).

  8 m/s in Rb vapor D. Budker *et al.*, Phys. Rev. Lett. **83**, 1767 (1999).

  45 m/s in Pr doped Y_2SiO_5 at 5 K A. V. Turukhin *et al.*, Phys. Rev. Lett. **88**, 023602 (2002).

Review of “Stopped” Light



- “Stopped” Light EIT
  - C. Liu, Z. Dutton, C.H. Behroozi, and L.V. Hau, Nature **409**, 490 (2001).
  - D.F. Phillips, A. Fleischhauer, A. Mair, and R.L. Walsworth, and M.D. Lukin, Phys. Rev. Lett. **86**, 783 (2001).
- Dynamically controlled photonic band gas.
  - M. Bajcsy, A.S. Zibrov, and M.D. Lukin, Nature **426**, 638 (2003).

Review of Superluminal Light

- Resonant Absorber

  S. Chu and S. Wong, Phys. Rev. Lett. 48 , 738 (1982).

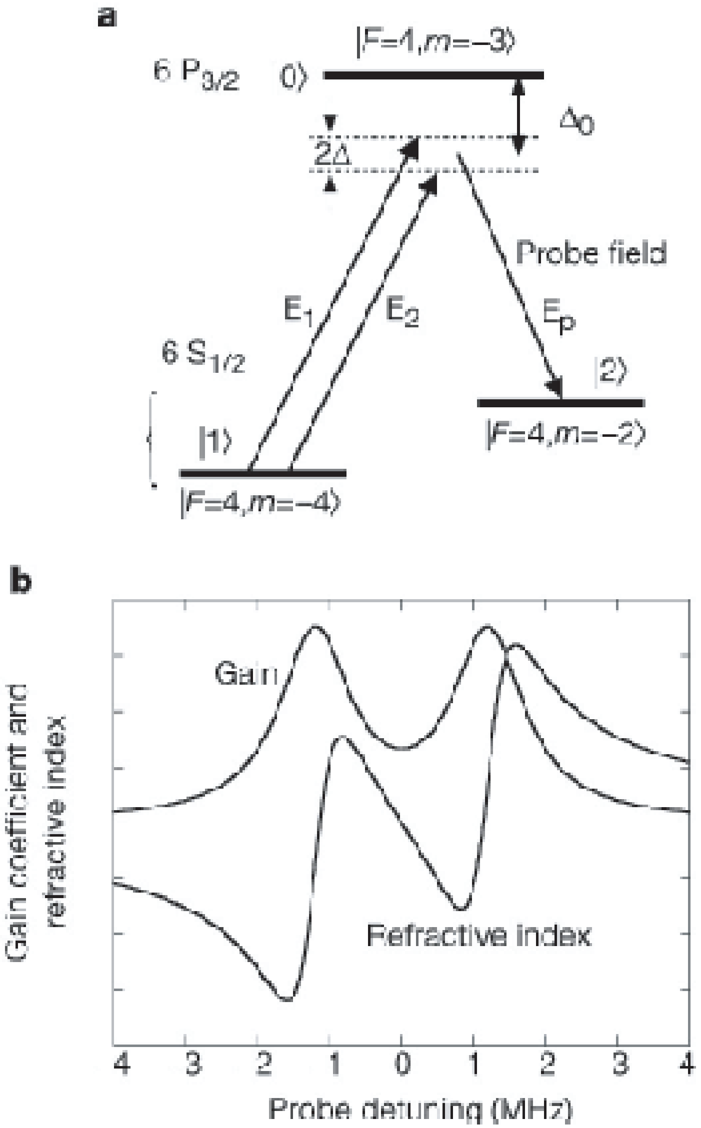
- EIA: $v_g = -c/23{,}000$

  A. V. Akulshin *et al.*, Phys. Rev. Lett. 83 , 4277 (1999).

- Gain-assisted superluminal light propagation

  L.J. Wang, A. Kuzmich, and A. Dogariu, Nature 406 , 277 (2000).

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



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

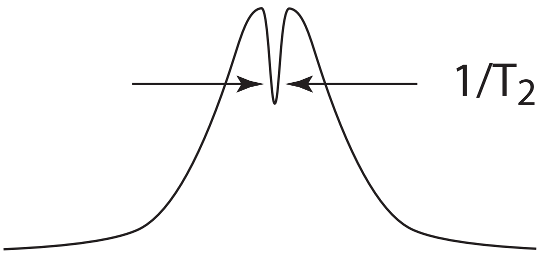
Need a large dn/dω. (How?)

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

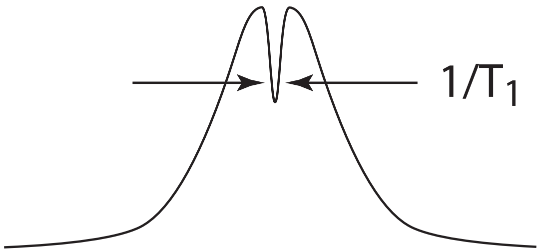
Well-known (to the few people how know it well) how to do so:

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

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



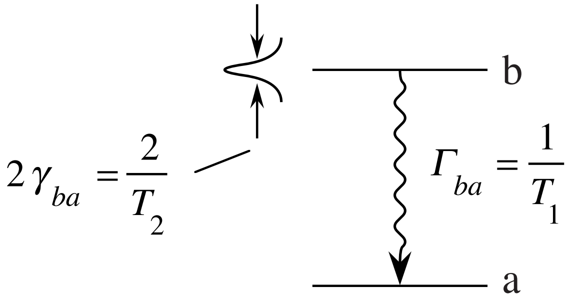
inhomogeneously
broadened medium

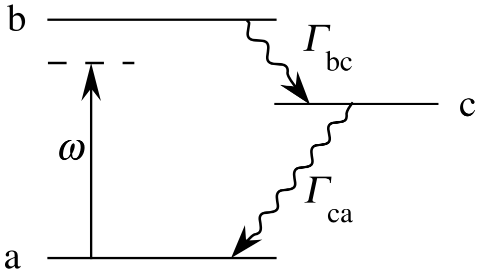


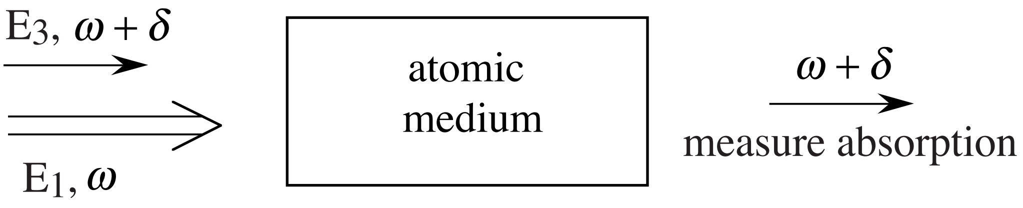
homogeneously
broadened medium
(or inhomogeneously
broadened)

PRL 90,113903(2003); see also news story in Nature.

Spectral Holes Due to Population Oscillations







atomic medium

measure absorption

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:

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

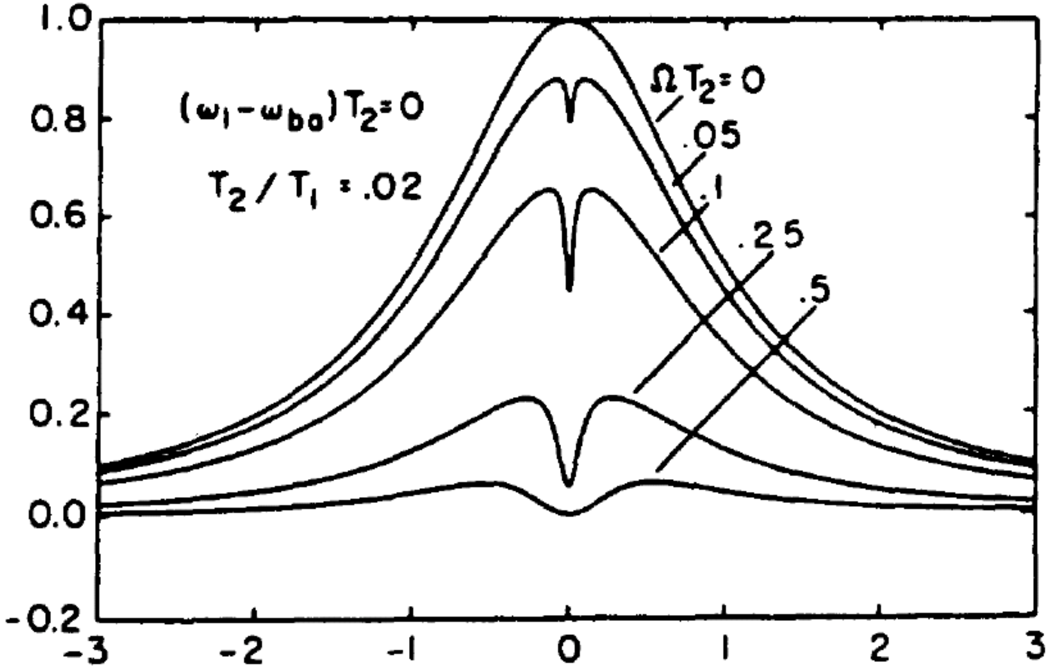
Probe-beam absorption:

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

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

Spectral Holes in Homogeneously Broadened Materials

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



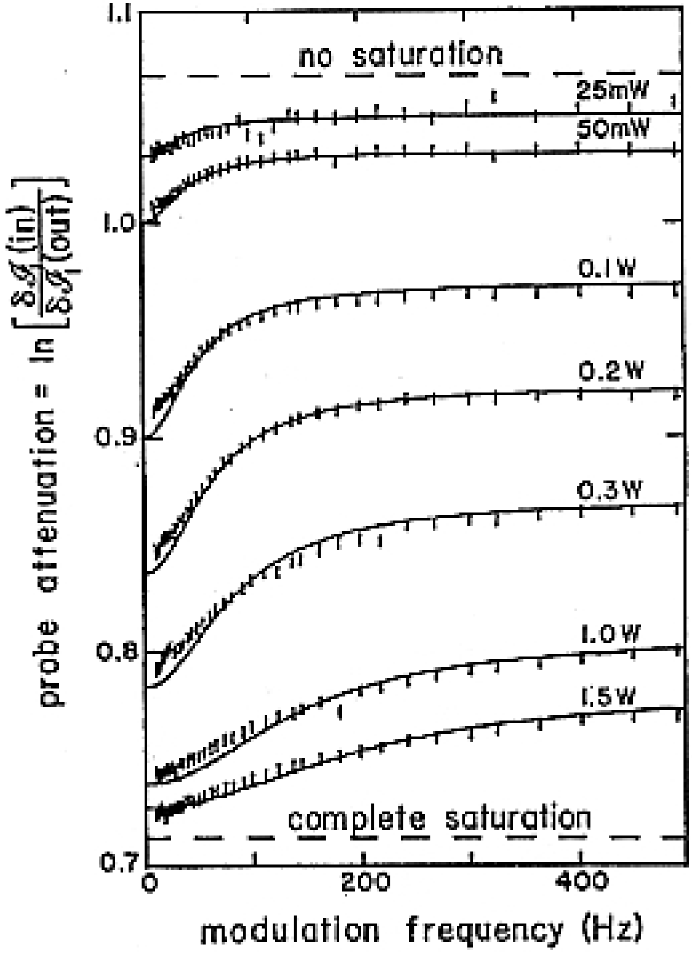
(pump-probe detuning) times T_2

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

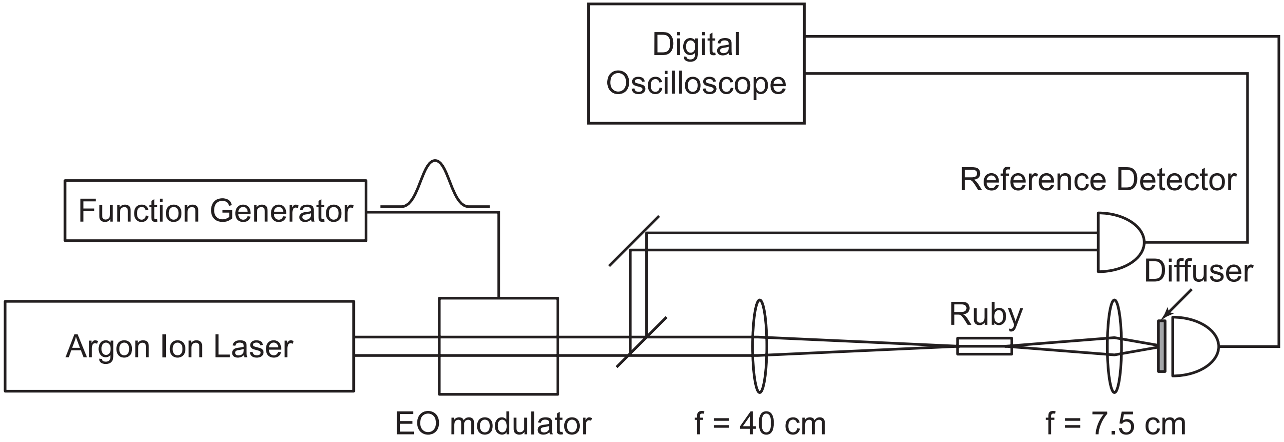
Volume 45, number 6 OPTICS COMMUNICATIONS 15 May 1983

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

Lloyd W. HILLMAN, Robert W. BOYD, Jerzy KRASINSKI and C.R. STROUD, Jr.
The Institute of Optics, University of Rochester, Rochester, NY 14627, USA

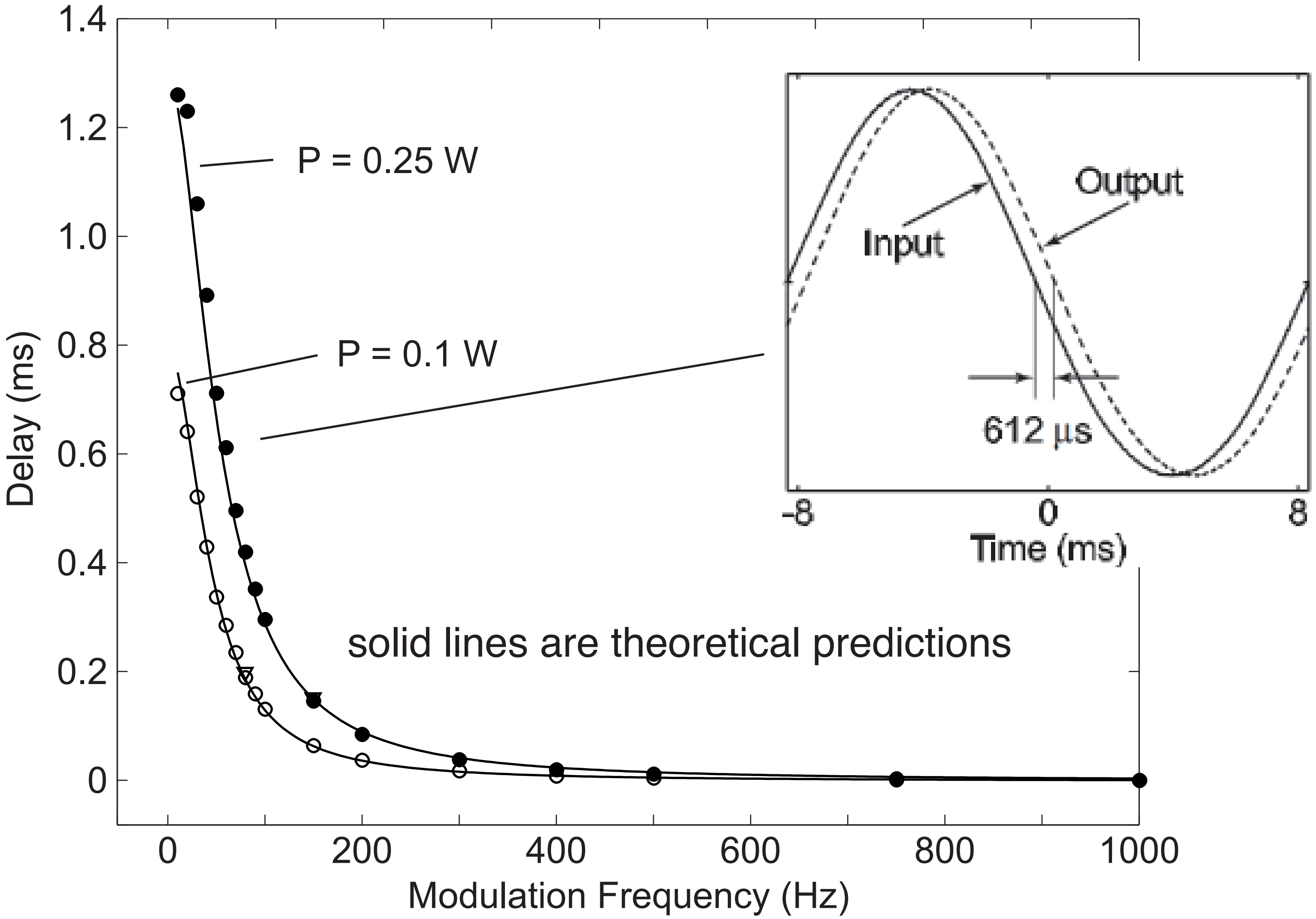


Experimental Setup Used to Observe Slow Light in Ruby



7.25 cm ruby laser rod (pink ruby)

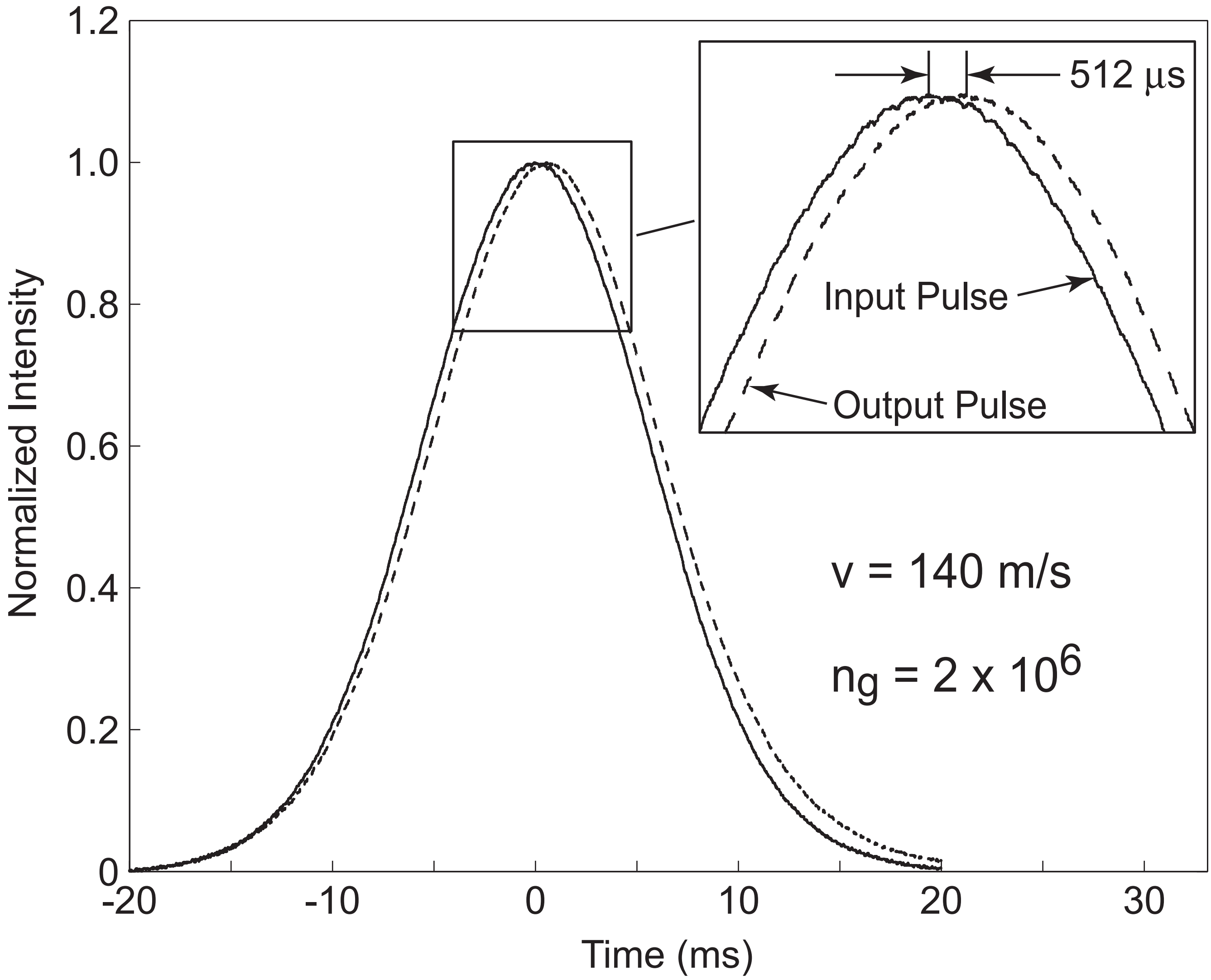
Measurement of Delay Time for Harmonic Modulation



solid lines are theoretical predictions

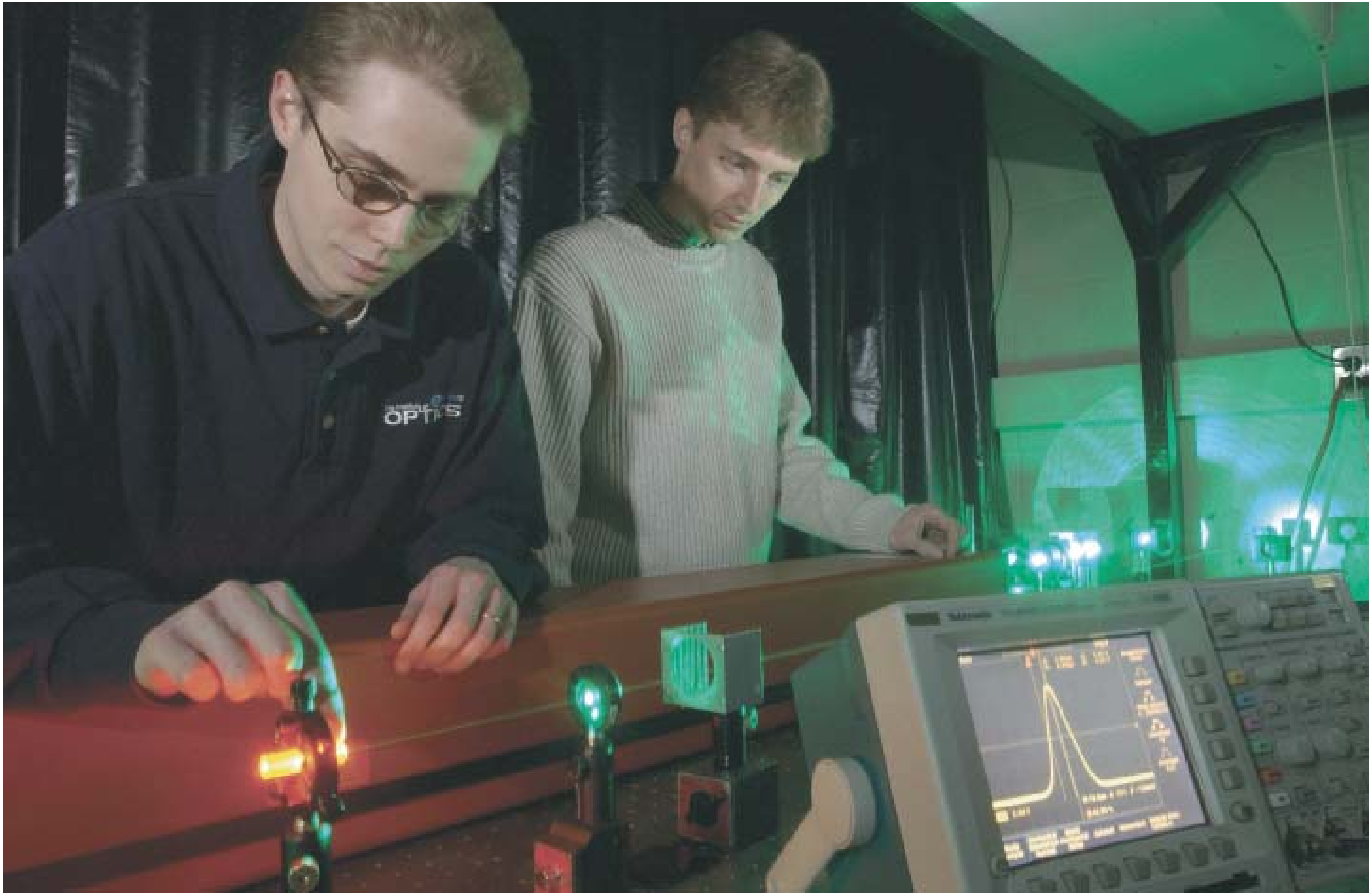
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

Gaussian Pulse Propagation Through Ruby

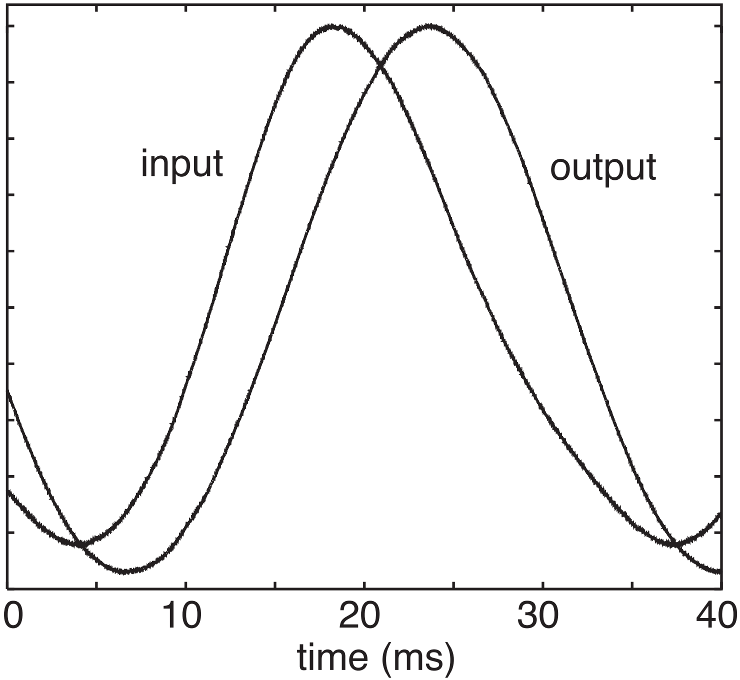


No pulse distortion!

Matt Bigelow and Nick Lepeshkin in the Lab



Slow Light in Ruby -- Greater Pulse Separation



Advantages of Coherent Population Oscillations for Slow Light

Works in solids

Works at room temperature

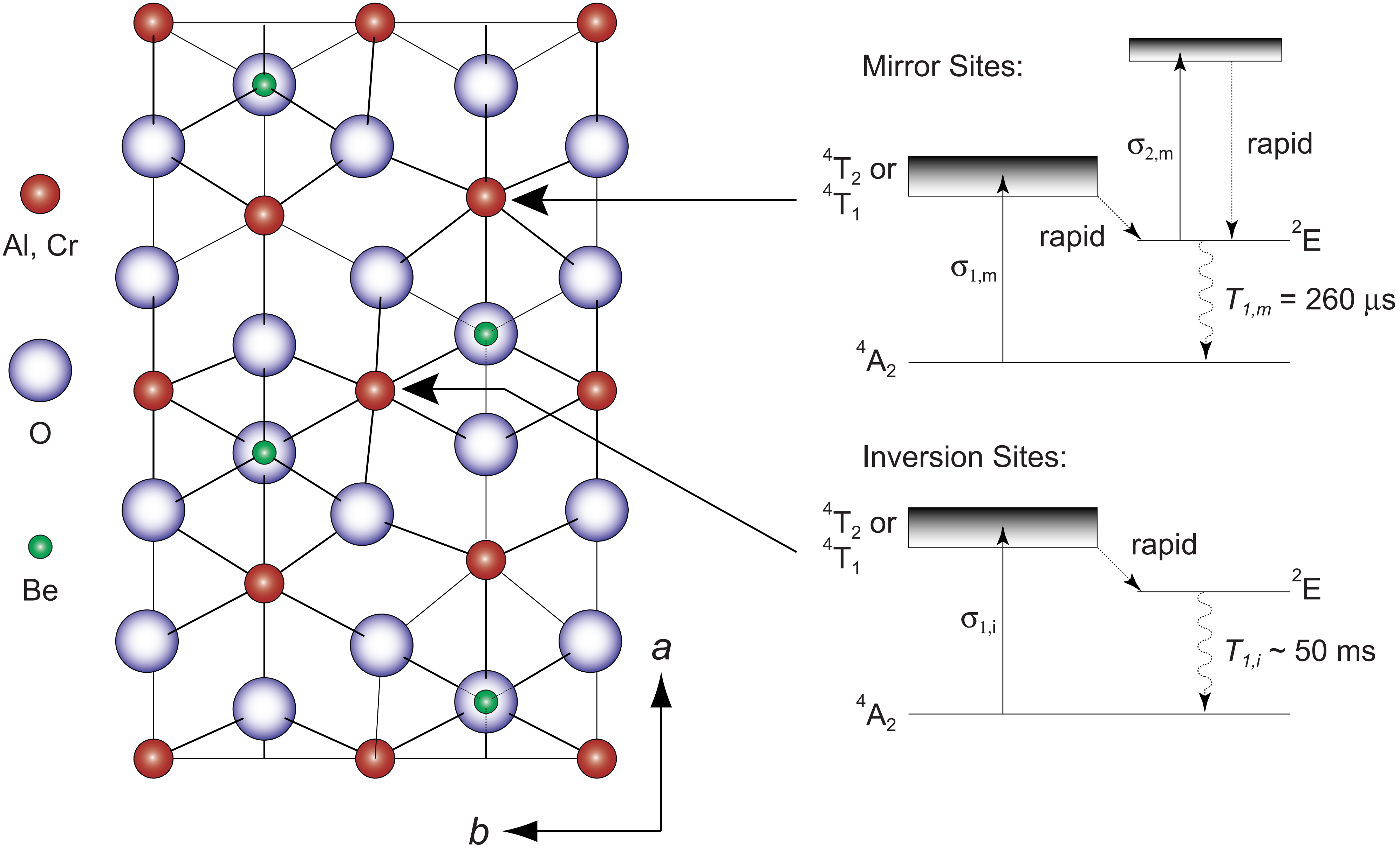
Insensitive of dephasing processes

Laser need not be frequency stabilized

Works with single beam (self-delayed)

Delay can be controlled through input intensity

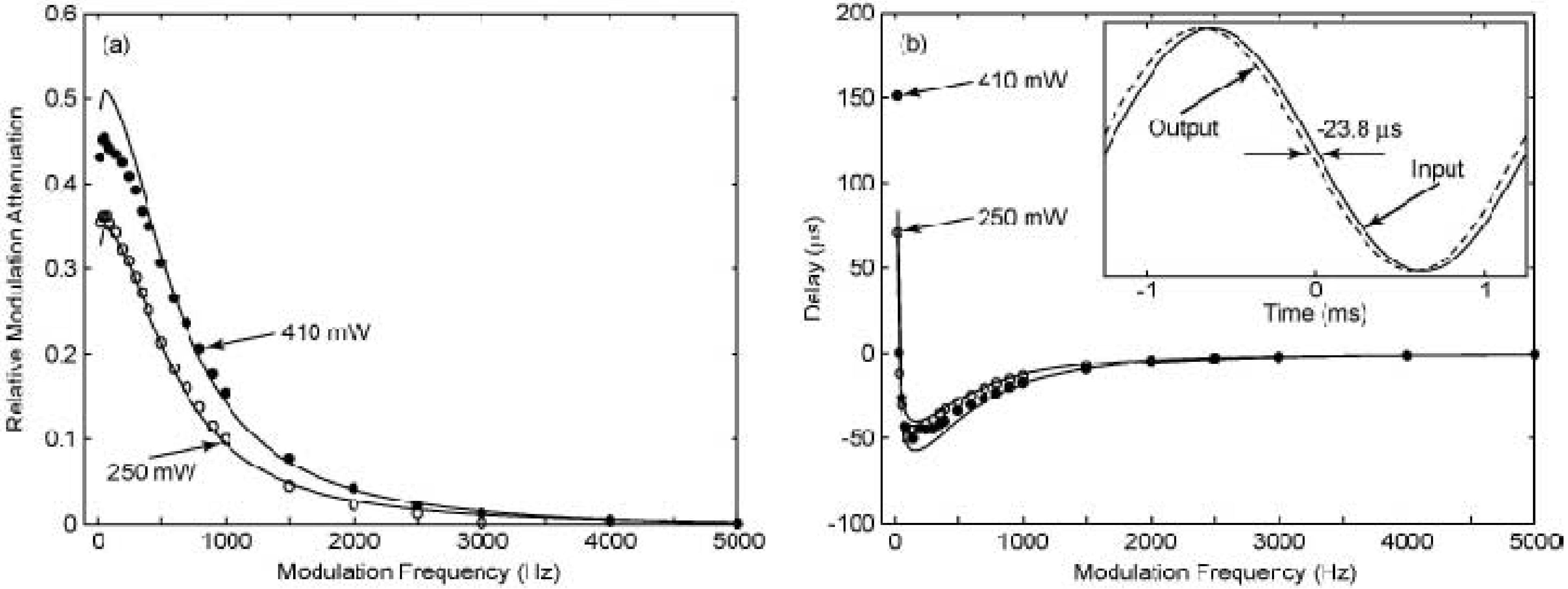
Alexandrite Displays both Saturable and Inverse-Saturable Absorption



Inverse-Saturable Absorption Produces Superluminal Propagation in Alexandrite

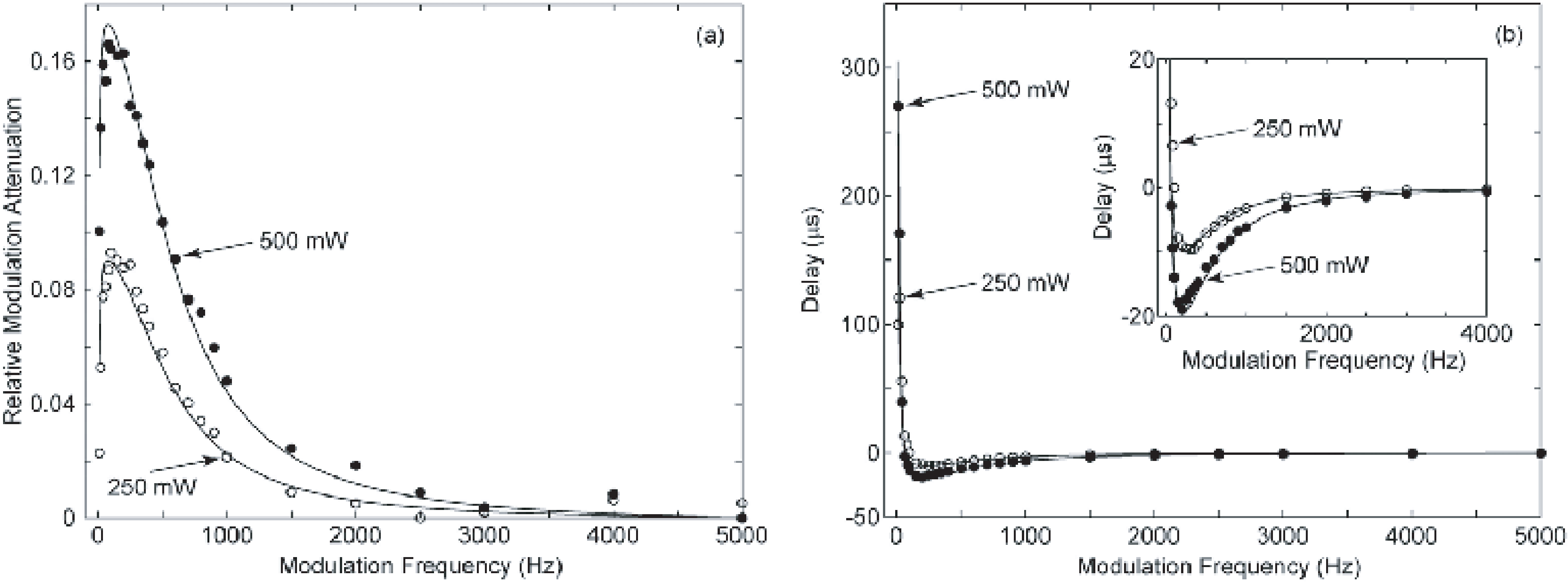
At 476 nm, alexandrite is an inverse saturable absorber

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



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

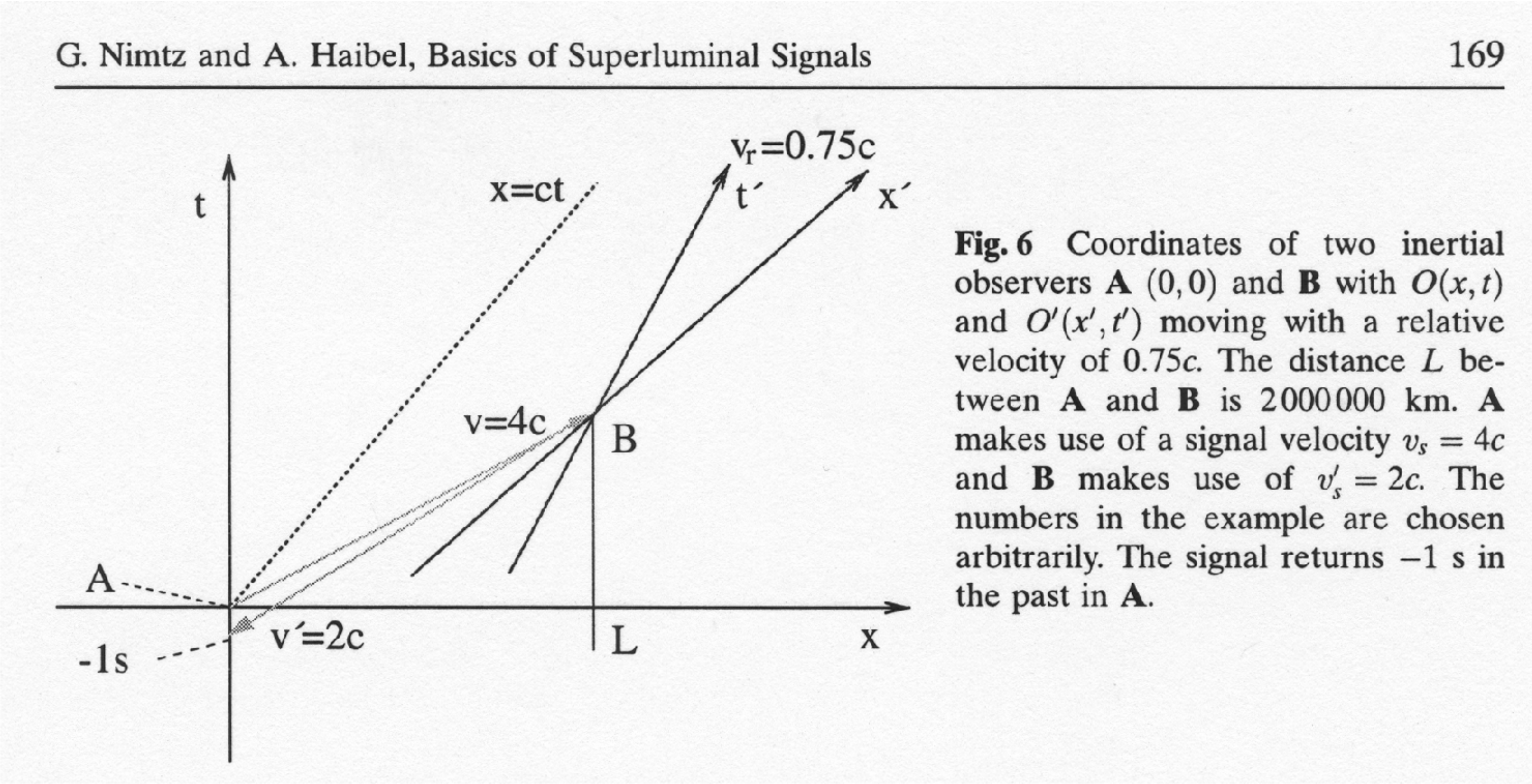
Probe Absorption and Delay at 488 nm



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

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!

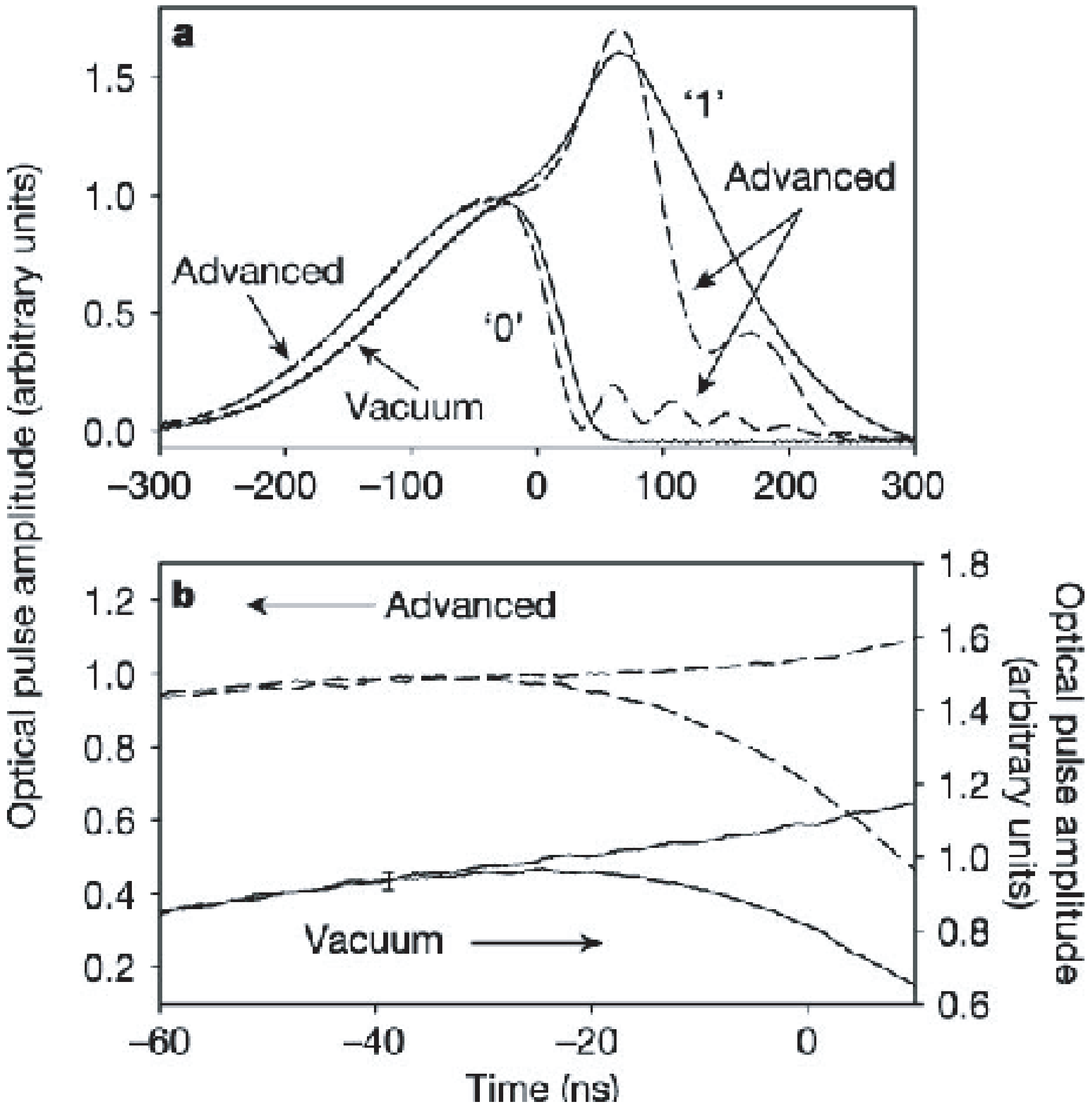
- What is information (or signal) velocity?

  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



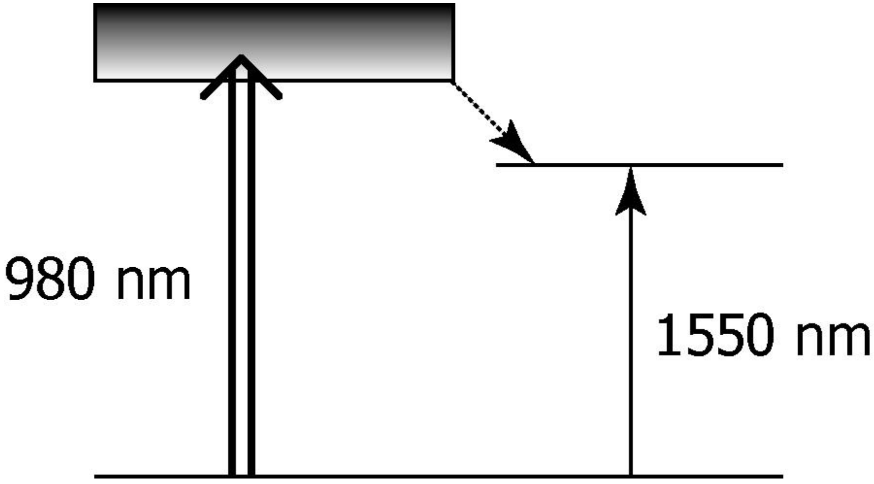
M.D. Stenner, D.J. Gauthier, and M.I. Neifeld, Nature,425 695 (2003).

Pulses are not distinguishable "early."

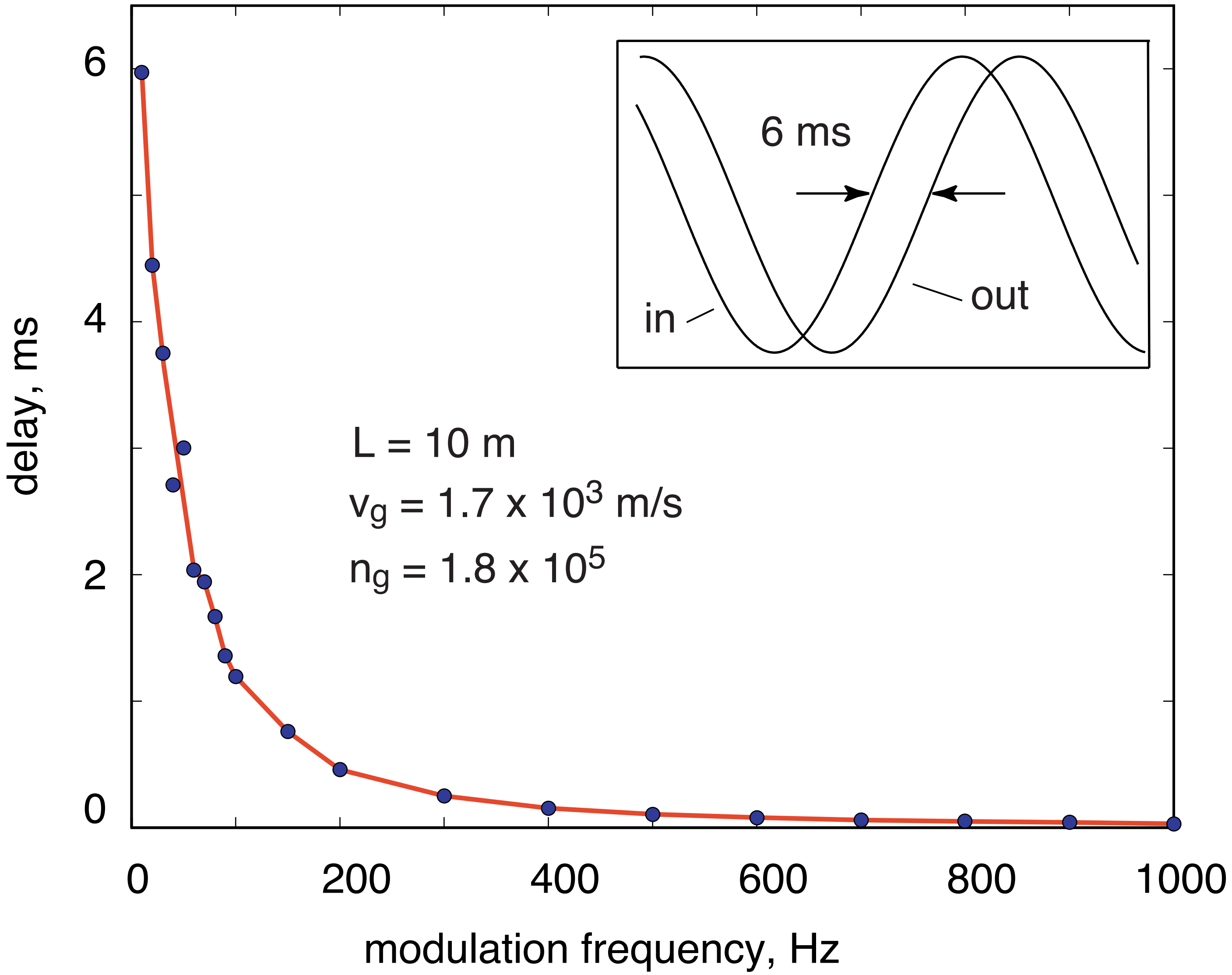
$v_i \leq c$

Slow and Fast Light in a Er-doped Fiber Amplifier

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

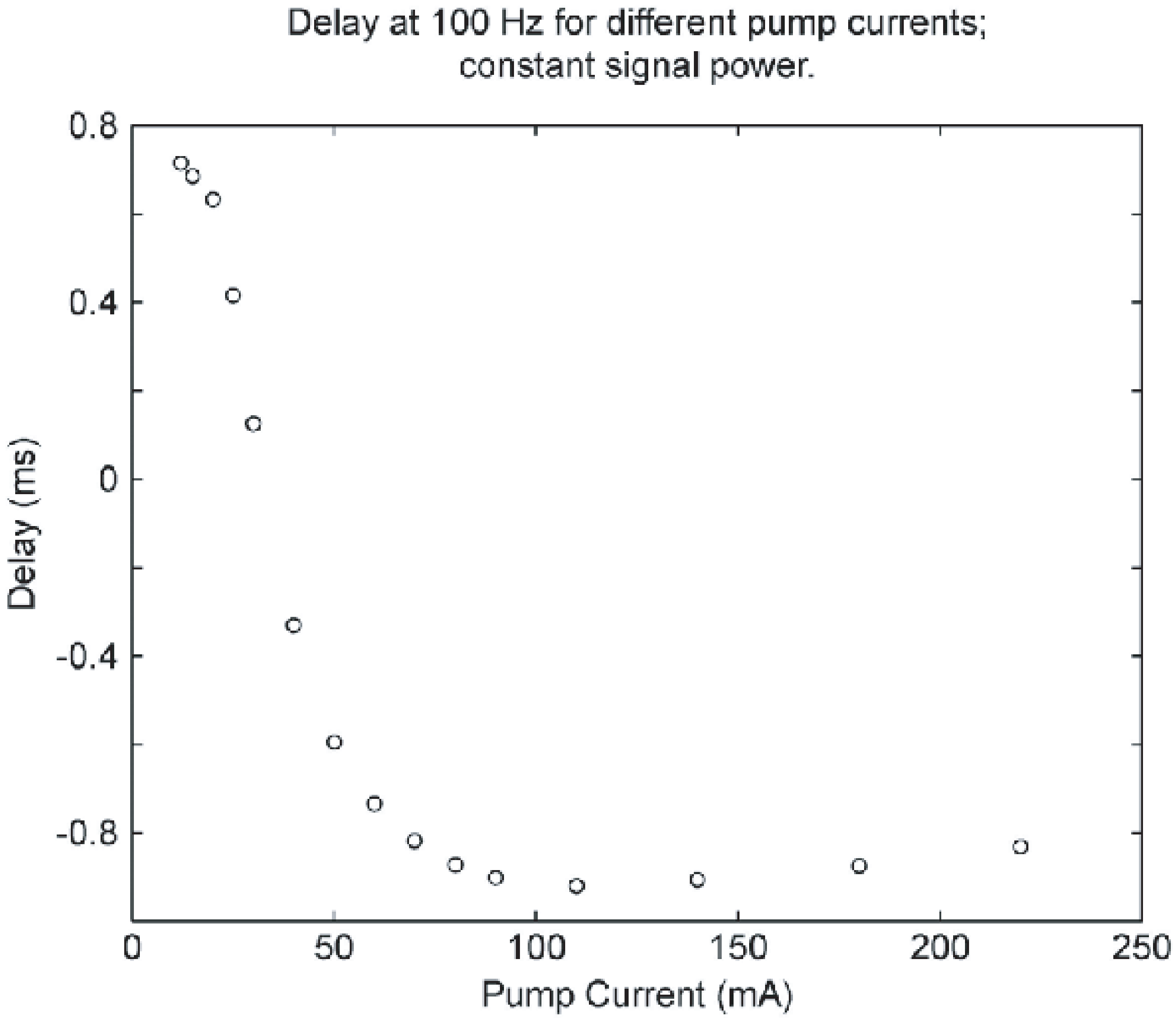


Slow Light in an Erbium-Doped Fiber Amplifier



with S. Jarabo, University of Zaragoza

Pump Power Dependence of Time Delay



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

Summary

- We have observed group velocities in ruby as low as 58 m/s.
- We have also observed slow and superluminal light propagation in alexandrite and in Er-doped fiber.
- Since this method is easy to implement and is insensitive to dephasing processes, it holds promise for applications.

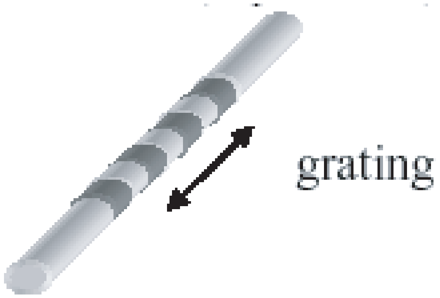
Related Work:

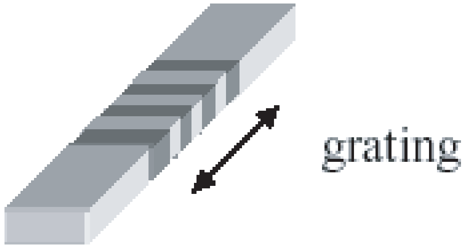
Slow Light in Structured Waveguides

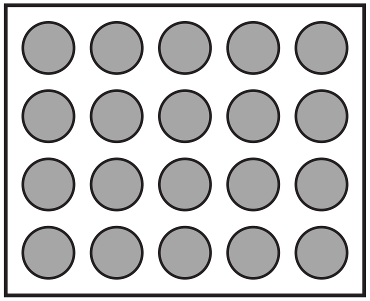
Artificial Materials for Nonlinear Optics

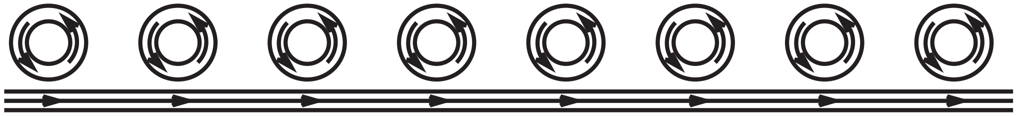
Artifical materials can produce
- Large nonlinear optical response
- Large dispersive effects

Examples
- Fiber/waveguide Bragg gratings
- PBG materials
- CROW devices (Yariv et al.)
- SCISSOR devices



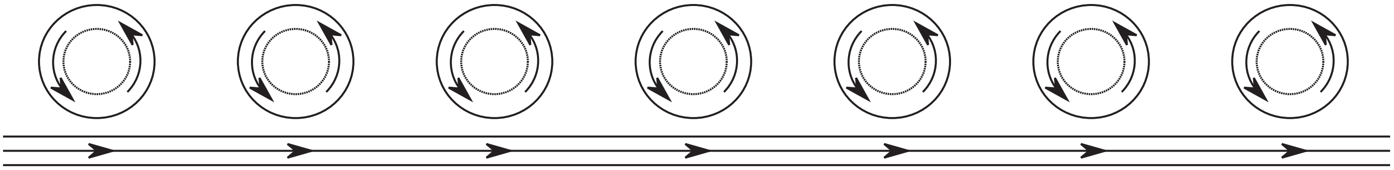






NLO of SCISSOR Devices

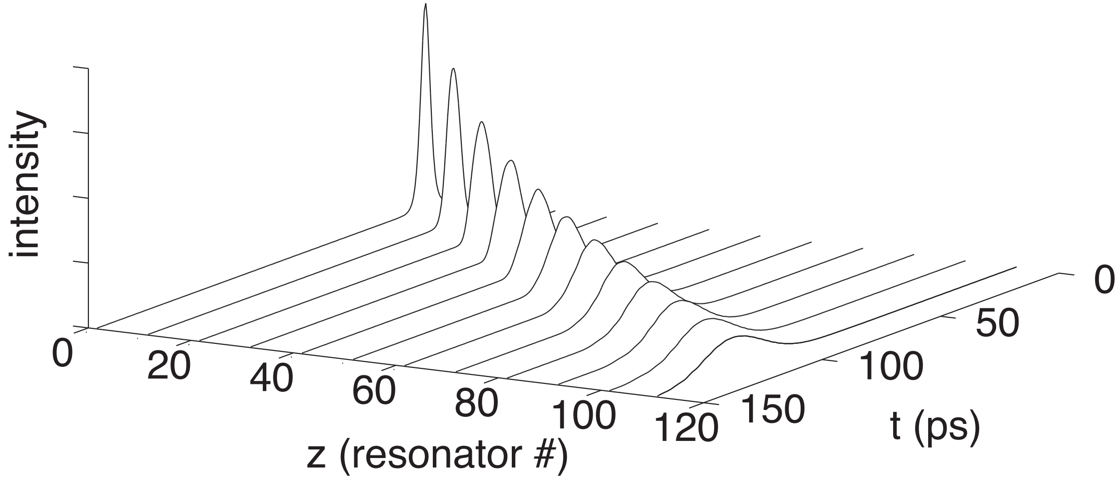
(Side-Coupled Integrated Spaced Sequence of Resonators)



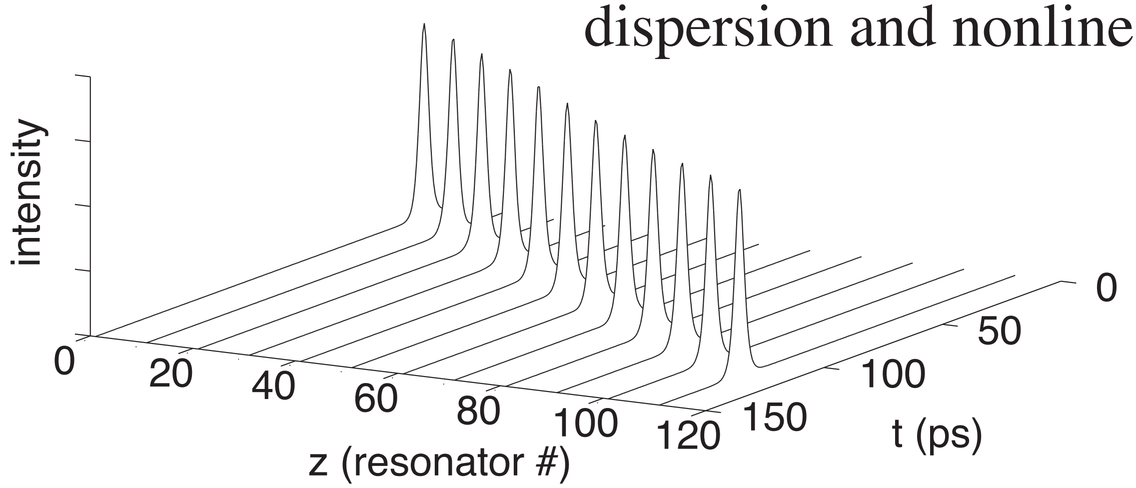
Shows slow-light, tailored dispersion, and enhanced nonlinearity

Optical solitons described by nonlinear Schrodinger equation

- Weak pulses spread because of dispersion

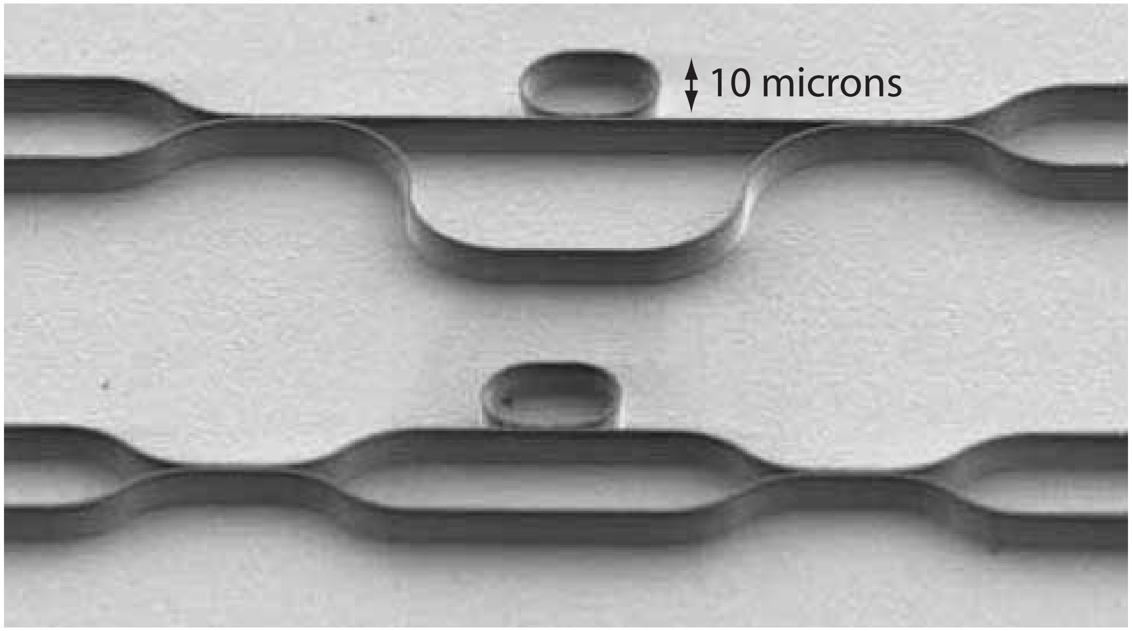


- But intense pulses form solitons through balance of dispersion and nonlinearity.



Microresonator-Based Photonic Devices

Resonator-Enhanced Mach-Zehnder Interferometers



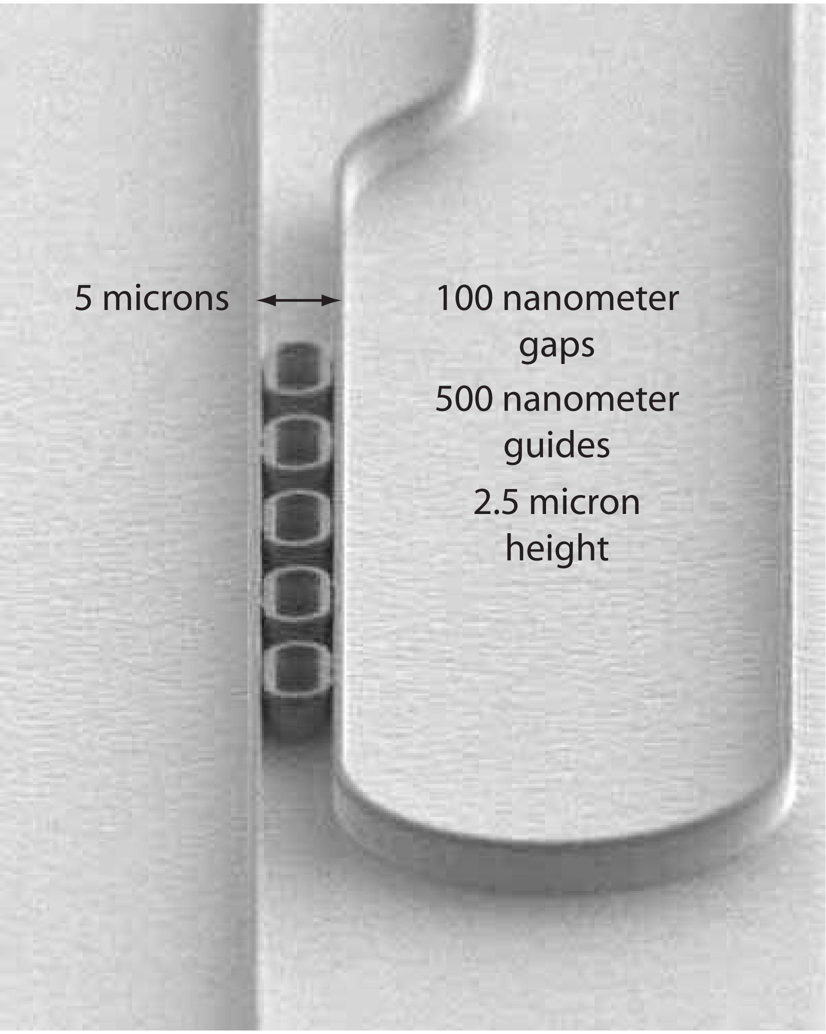
~100 nanometer gaps

500 nanometer guides

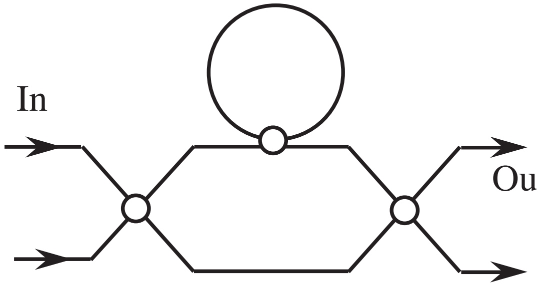
2.5 micron height

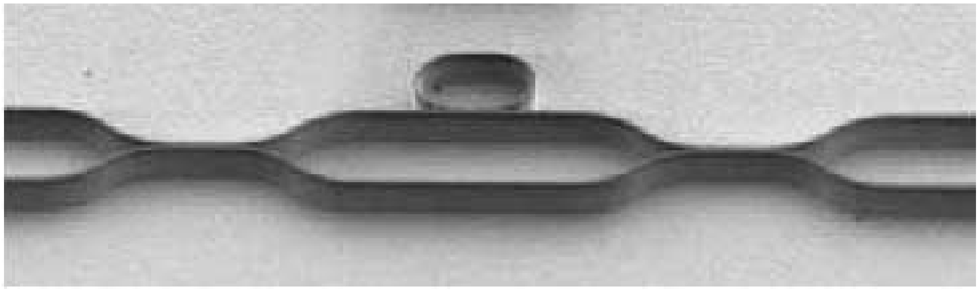
J. E. Heebner et. al, Optics Letters, 2004

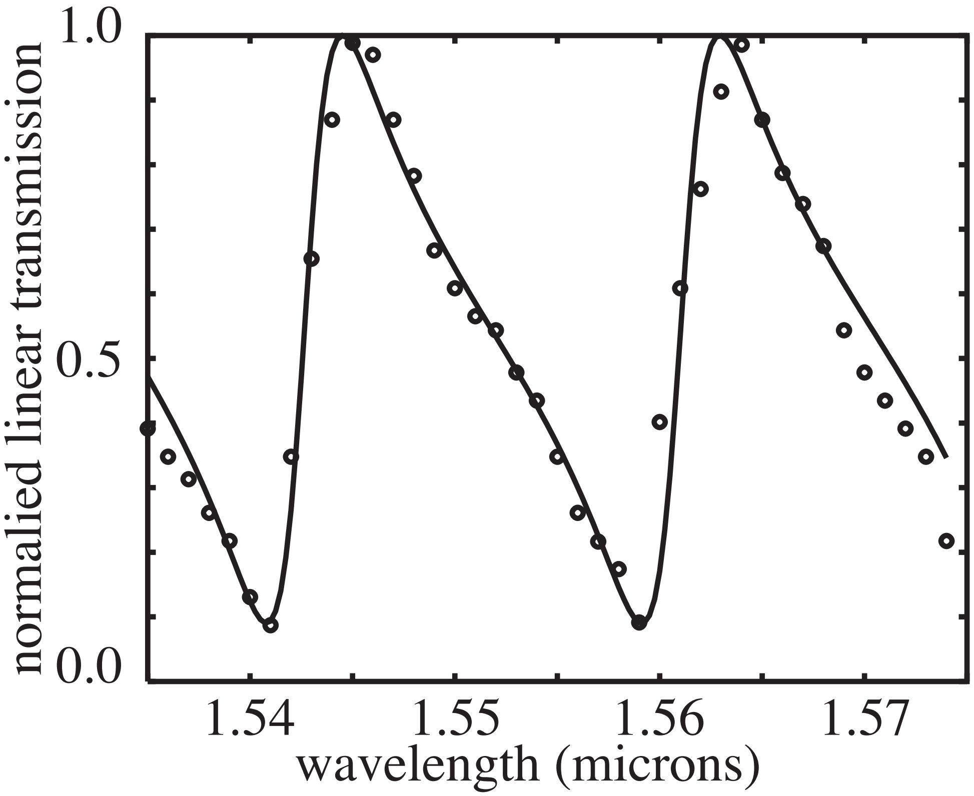
Five-Cell SCISSOR with Tap Channel

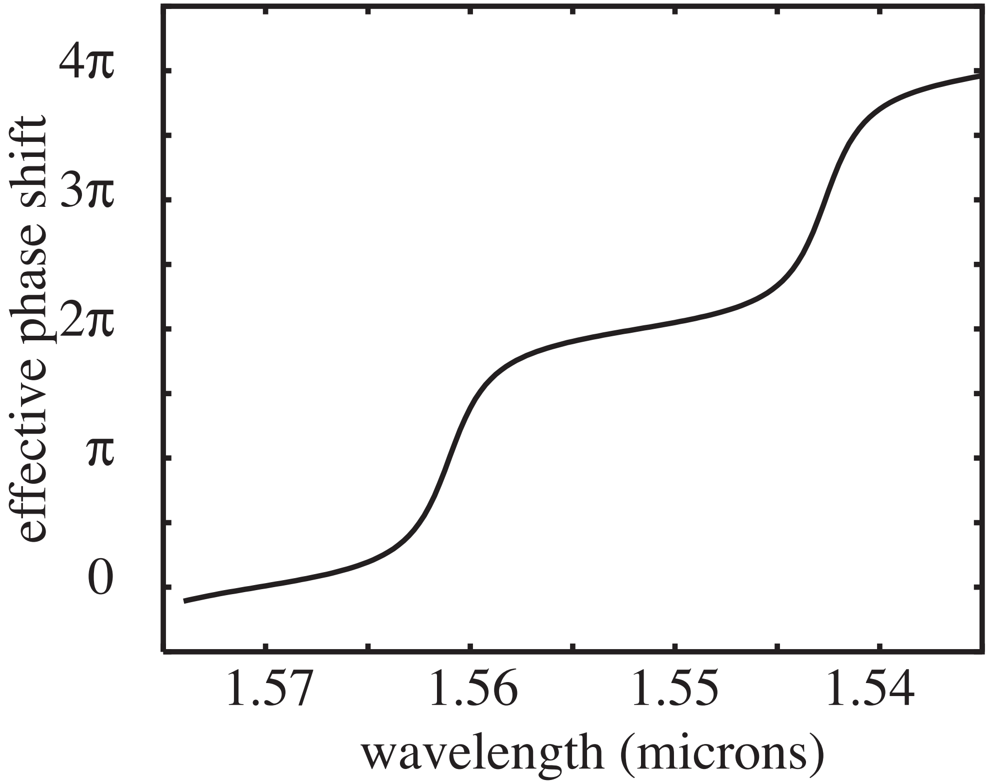


Phase Characteristics of Micro-Ring Resonator



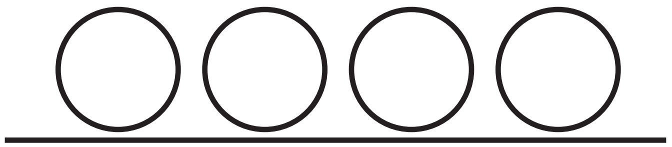



transmission

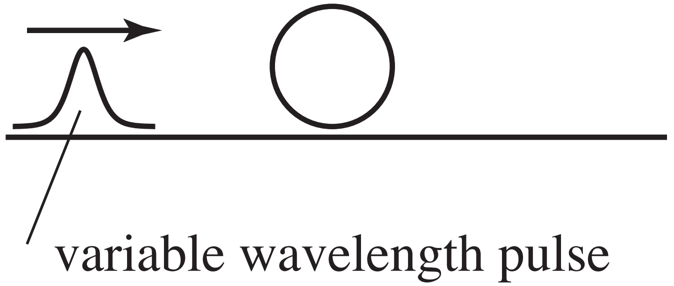

induced phase shift

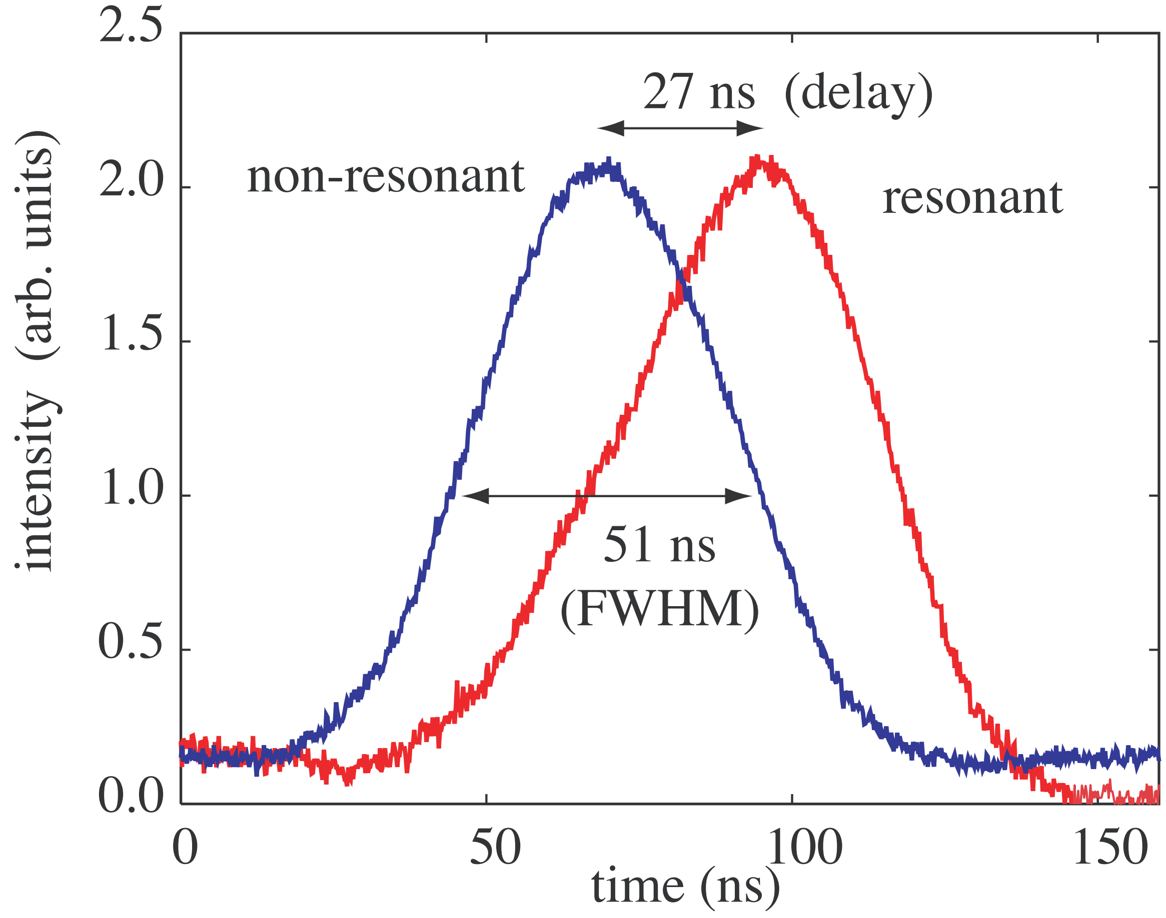
Fiber-Resonator Optical Delay Line

Fiber optical delay line:



First study one element of optical delay line:





with Deborah Jackson, JPL

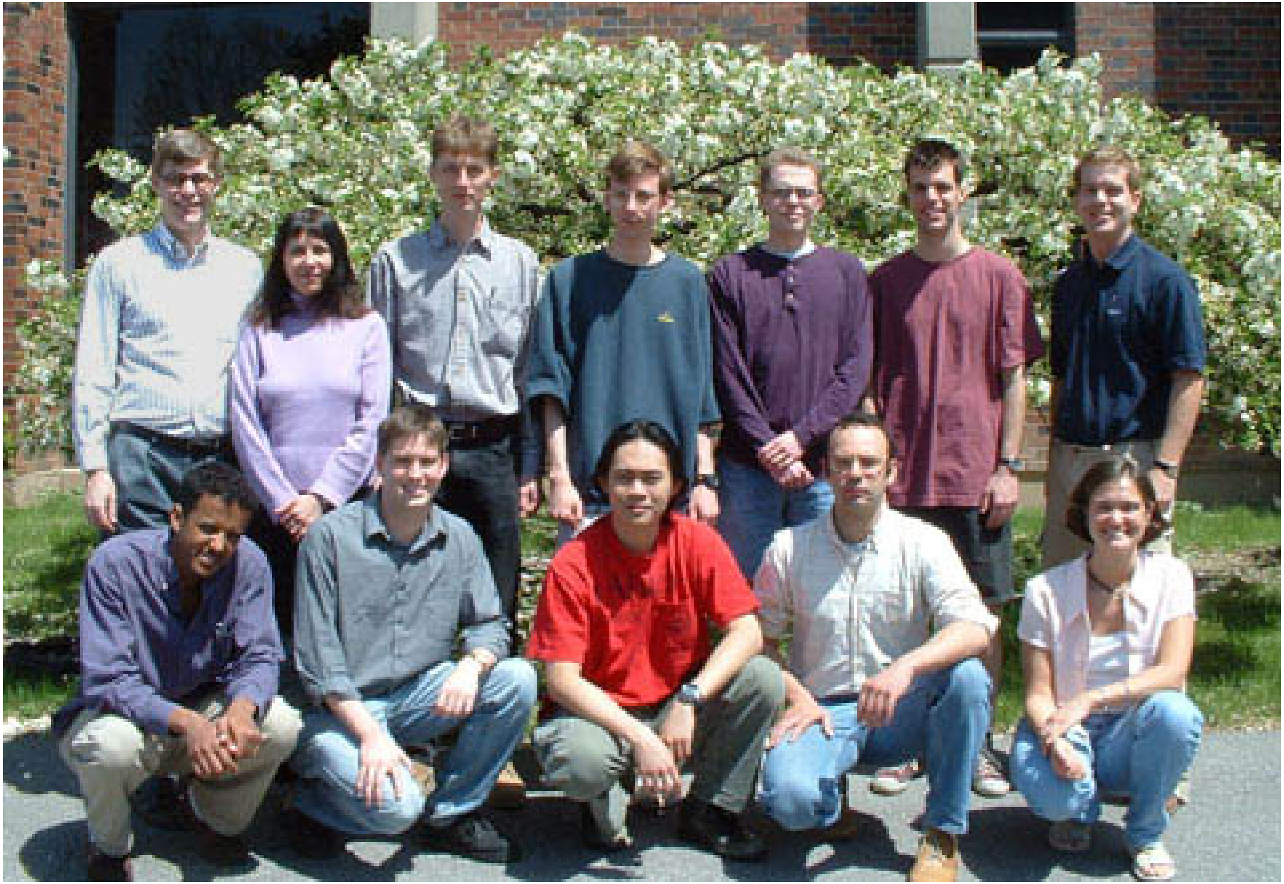
Summary

Demonstration of room temperature superluminal propagation in alexandrite and erbium and slow light propagation in ruby

Artificial materials hold great promise for applications in photonics because of

- large controllable nonlinear response
- large dispersion controllable in magnitude and sign

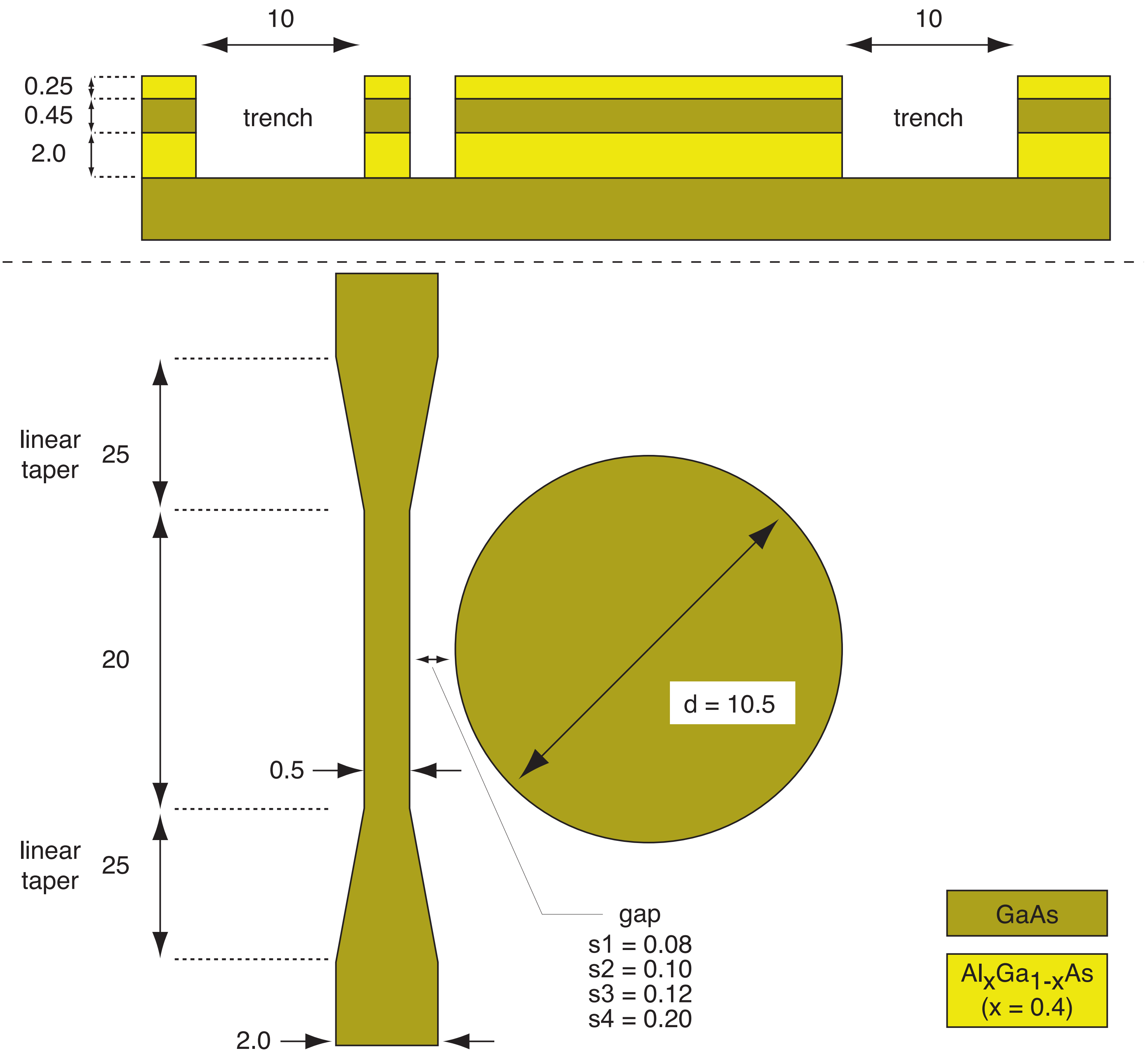
Special Thanks to my Students and Research Associates



Thank you for your attention.

Microdisk Resonator Design

All dimensions in microns



J. E. Heebner and R. W. Boyd

Photonic Device Fabrication Procedure

(1) MBE growth

(2) Deposit oxide

(3) Spin-coat e-beam resist

(4) Pattern inverse with e-beam & develop

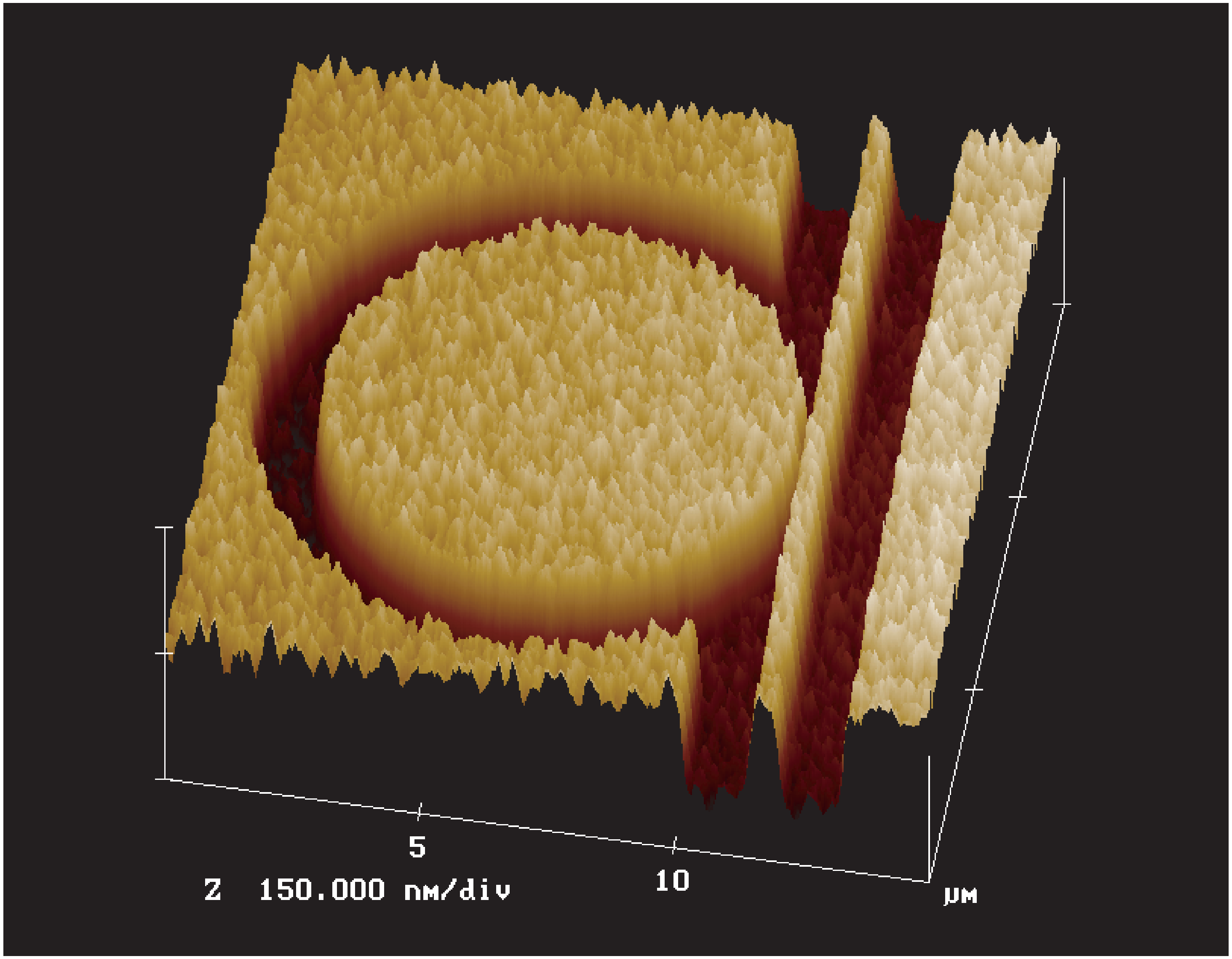
(5) RIE etch oxide

(6) Remove PMMA

(7) CAIBE etch AlGaAs-GaAs

(8) Strip oxide

Disk Resonator and Optical Waveguide in PMMA Resist



AFM

All-Optical Switching in a Microresonator-Enhanced Mach-Zehnder Interferometer