

Slow, Fast, and Backwards Light Propagation in Erbium-Doped Optical Fibers

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with George Gehring, Daniel Gauthier, Giovanni Piredda, Paul Narum,
Aaron Schweinsberg, Zhimin Shi, Heedeuk Shin, Joseph Vornehm,
Petros Zerom, and many others

Presented at the OSA Topical Meeting on Nonlinear Optics, August 1, 2007

Interest in Slow Light

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

Fundamentals of optical physics

Optical delay lines, optical storage, optical memories

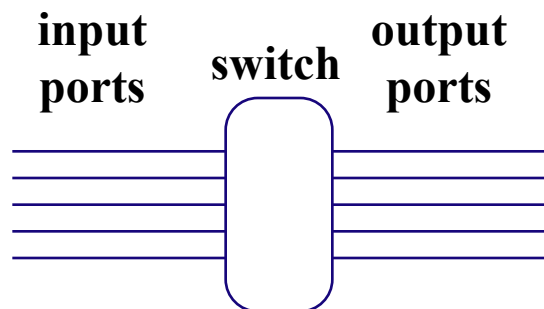
Implications for quantum information

What about fast light ($v > c$) and backwards light (v negative)?

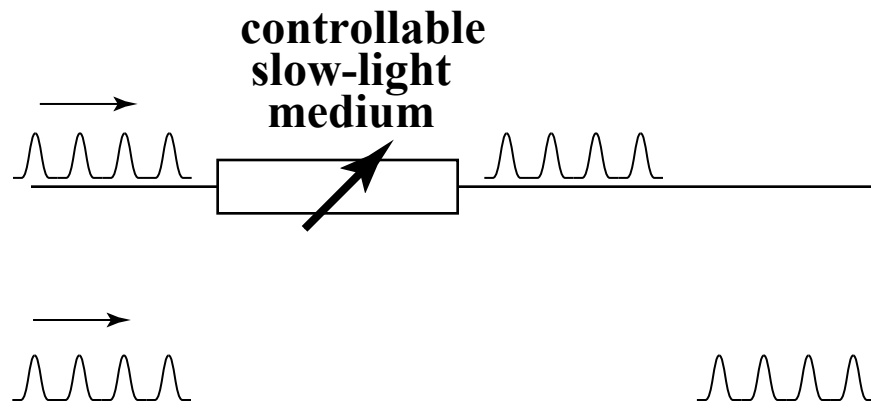
Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.



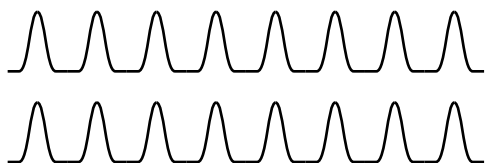
All-Optical Switch



Use Optical Buffering to Resolve Data-Packet Contention



But what happens if two data packets arrive simultaneously?

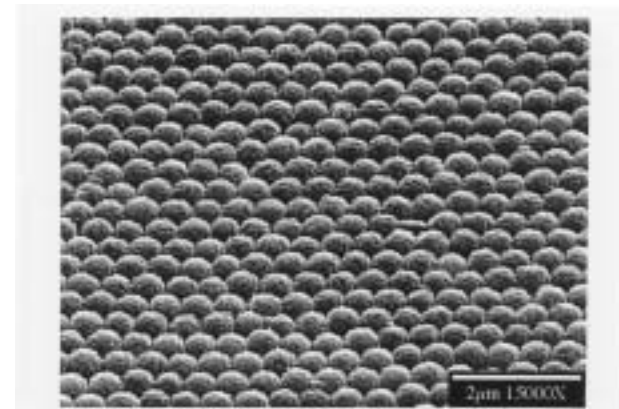


Controllable slow light for optical buffering can dramatically increase system performance.

Some Approaches to Slow Light Propagation

- Use the linear response of atomic systems
or (better)
use quantum coherence (e.g., electromagnetically induced transparency) to modify and control this response
- Use of artificial materials (to modify the optical properties at the macroscopic level)

E.g., photonic crystals where strong spectral variation of the refractive index occurs near the edge of the photonic bandgap



polystyrene photonic crystal

Slow and Fast Light and Optical Resonances

Pulses propagate at the group velocity given by

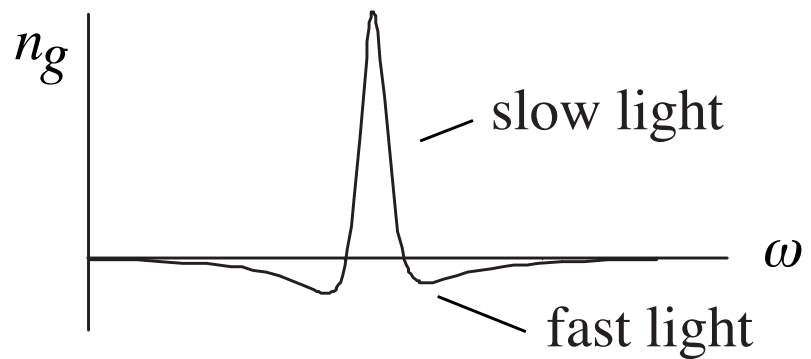
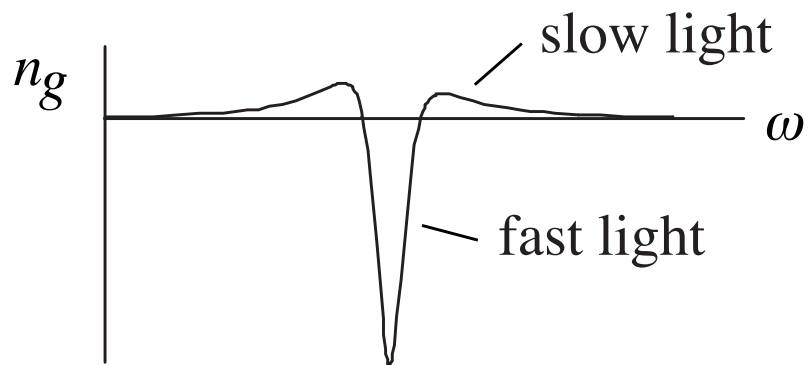
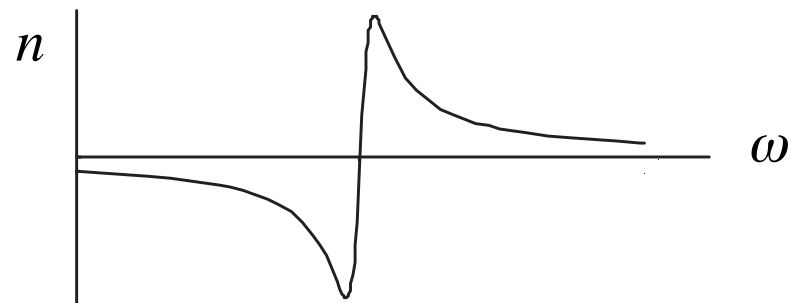
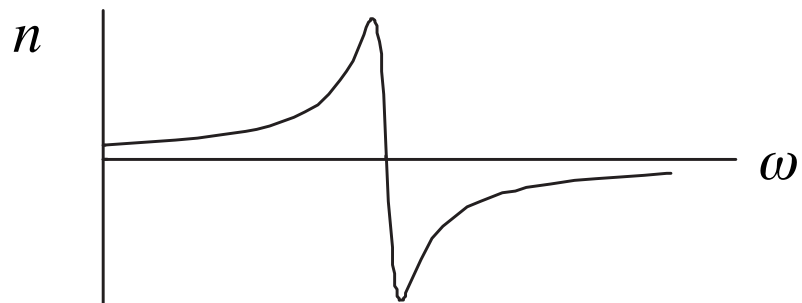
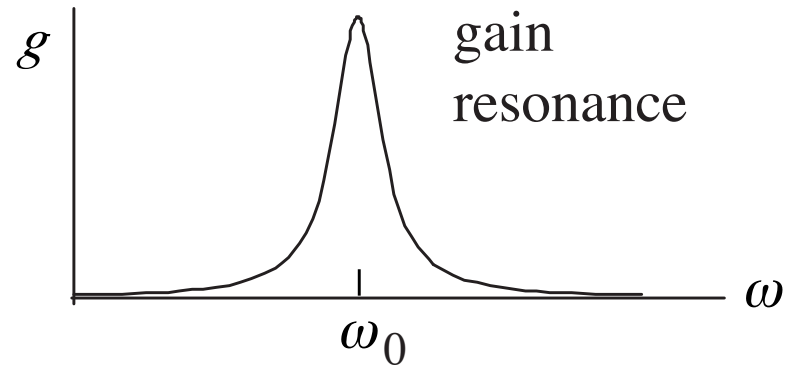
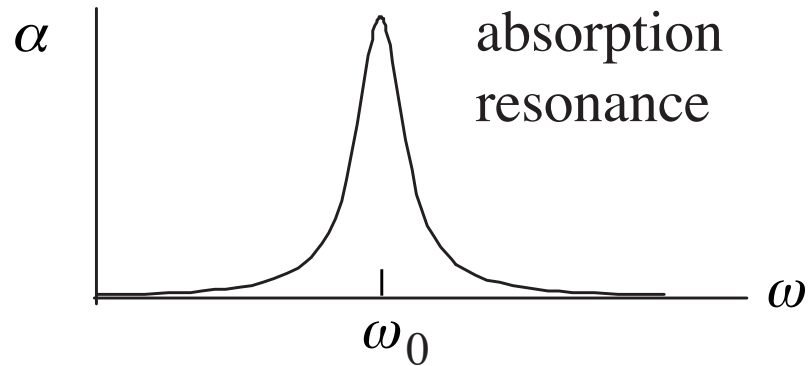
$$v_g = \frac{c}{n_g} \quad n_g = n + \omega \frac{dn}{d\omega}$$

Want large dispersion to obtain extreme group velocities

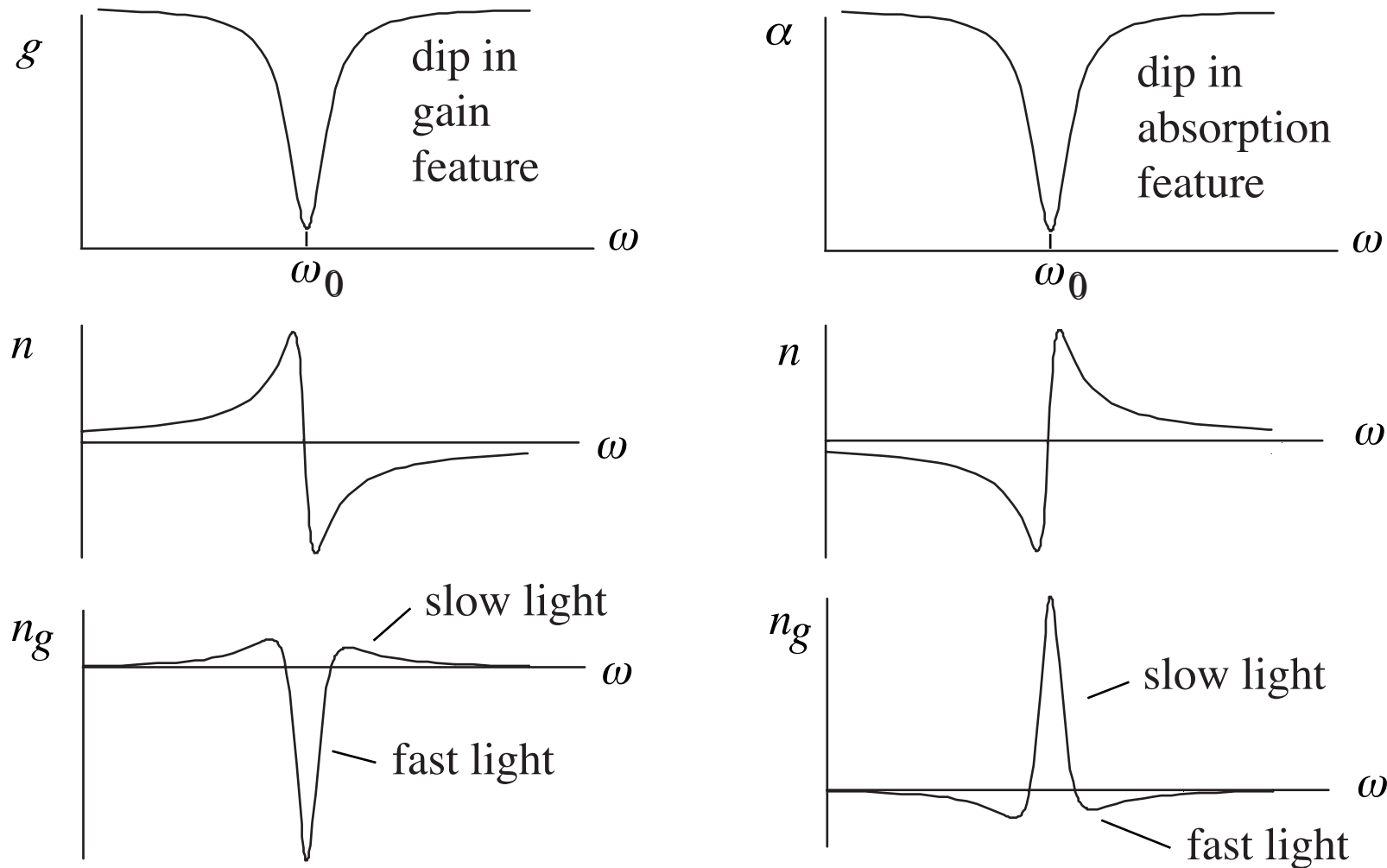
Sharp spectral features produce large dispersion.

The group index can be large and positive (slow light), positive and much less than unity (fast light) or negative (backwards light).

How to Create Slow and Fast Light I – Use Isolated Gain or Absorption Resonance



How to Create Slow and Fast Light II – Use Dip in Gain or Absorption Feature



Narrow dips in gain and absorption lines can be created by various nonlinear optical effects, such as electromagnetically induced transparency (EIT), coherent population oscillations (CPO), and conventional saturation.

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

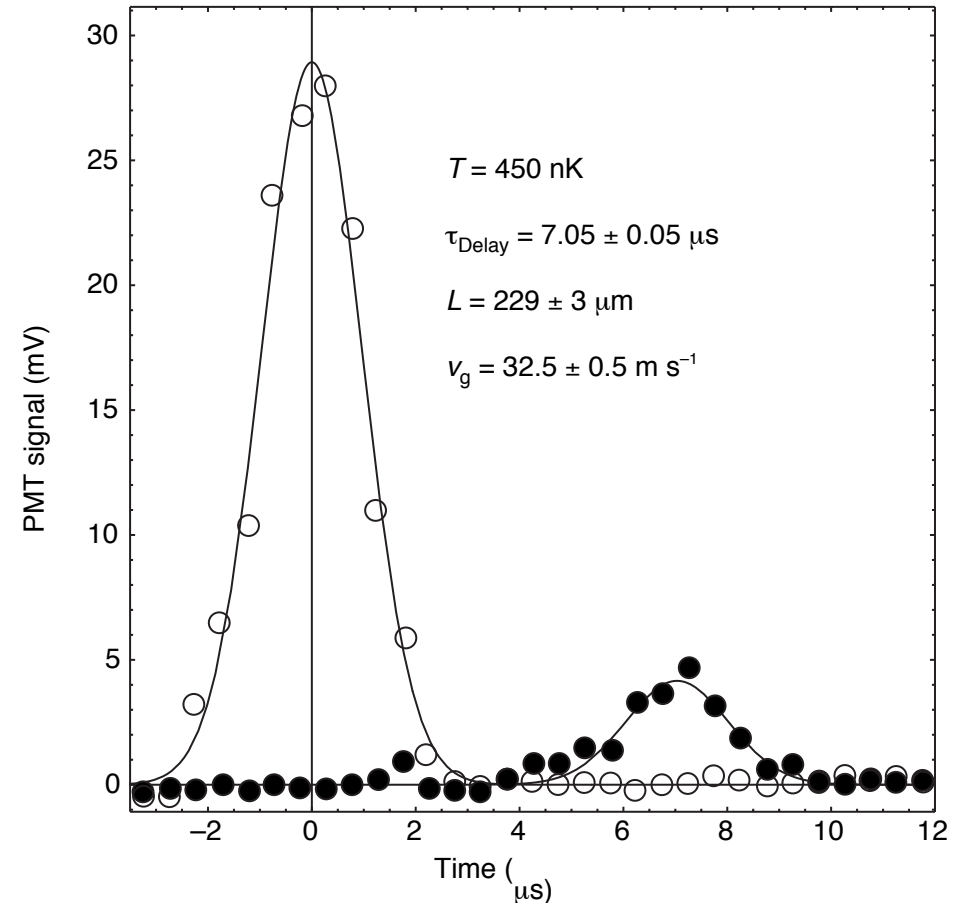
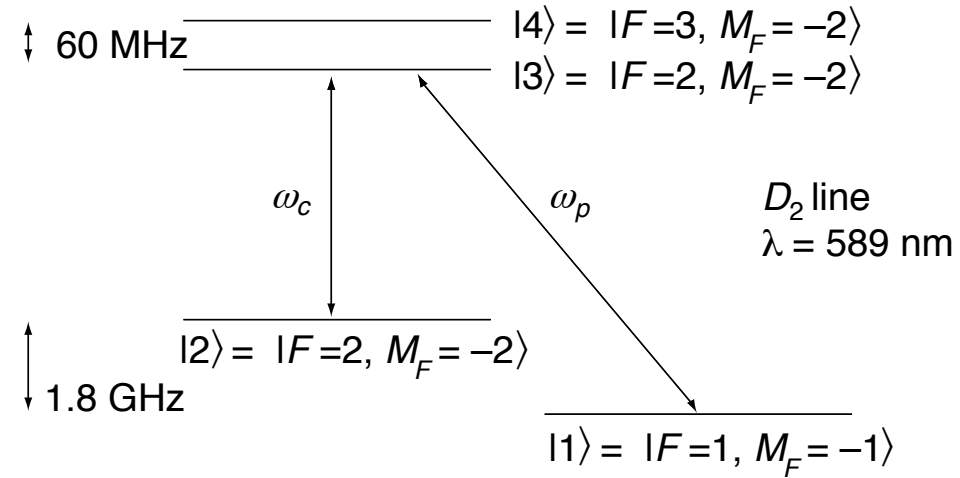
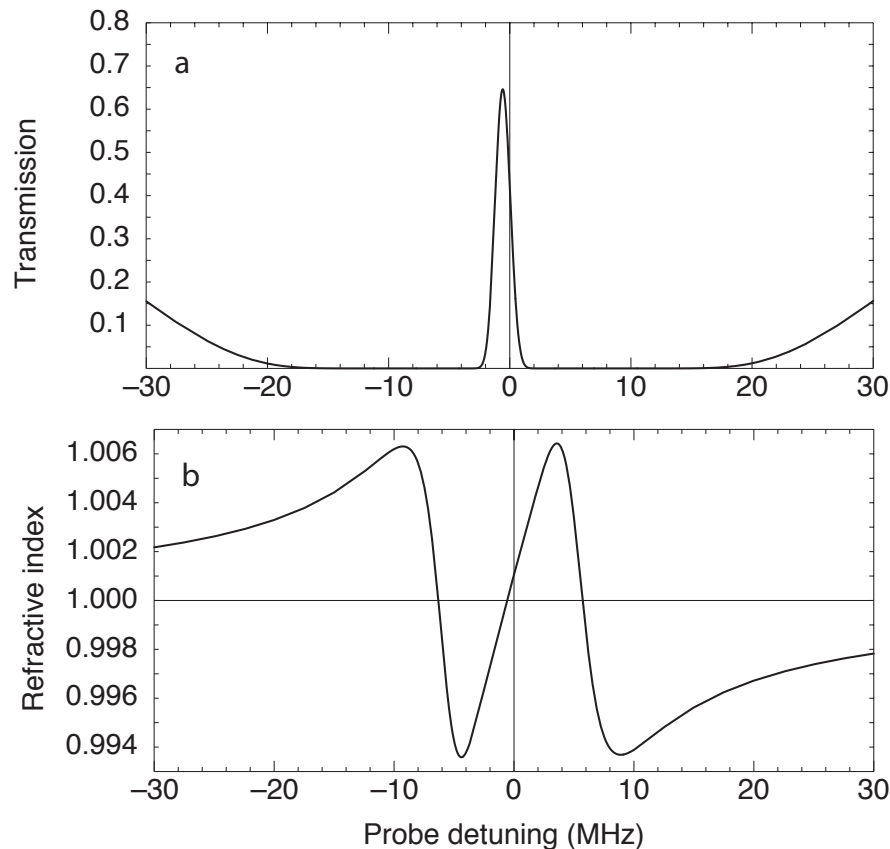
Lene Vestergaard Hau^{*2}, S. E. Harris³, Zachary Dutton^{*2}
& Cyrus H. Behroozi^{*§}

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

² Department of Physics, [§] Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

³ Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA

NATURE | VOL 397 | 18 FEBRUARY 1999 | www.nature.com



Challenge / Goal (2003)

Slow light in a room-temperature, solid-state material.

Our solution:

Slow light *via* coherent population oscillations (CPO), a quantum coherence effect related to EIT but which is less sensitive to dephasing processes.

Slow Light in Ruby

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

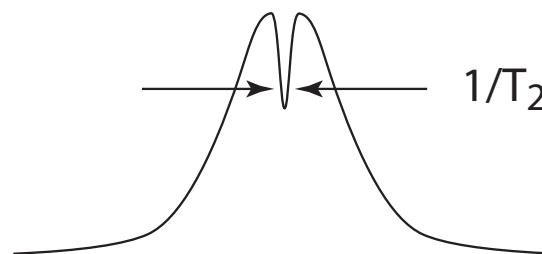
Kramers-Kronig relations:

Want a very narrow feature in absorption line.

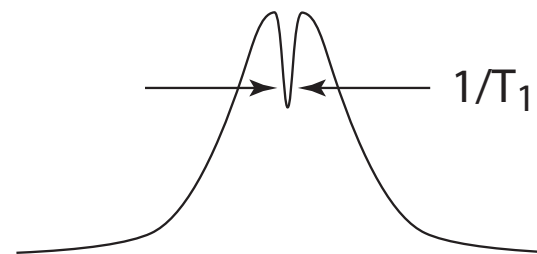
Well-known “trick” for doing so:

Make use of spectral holes due to population oscillations.

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

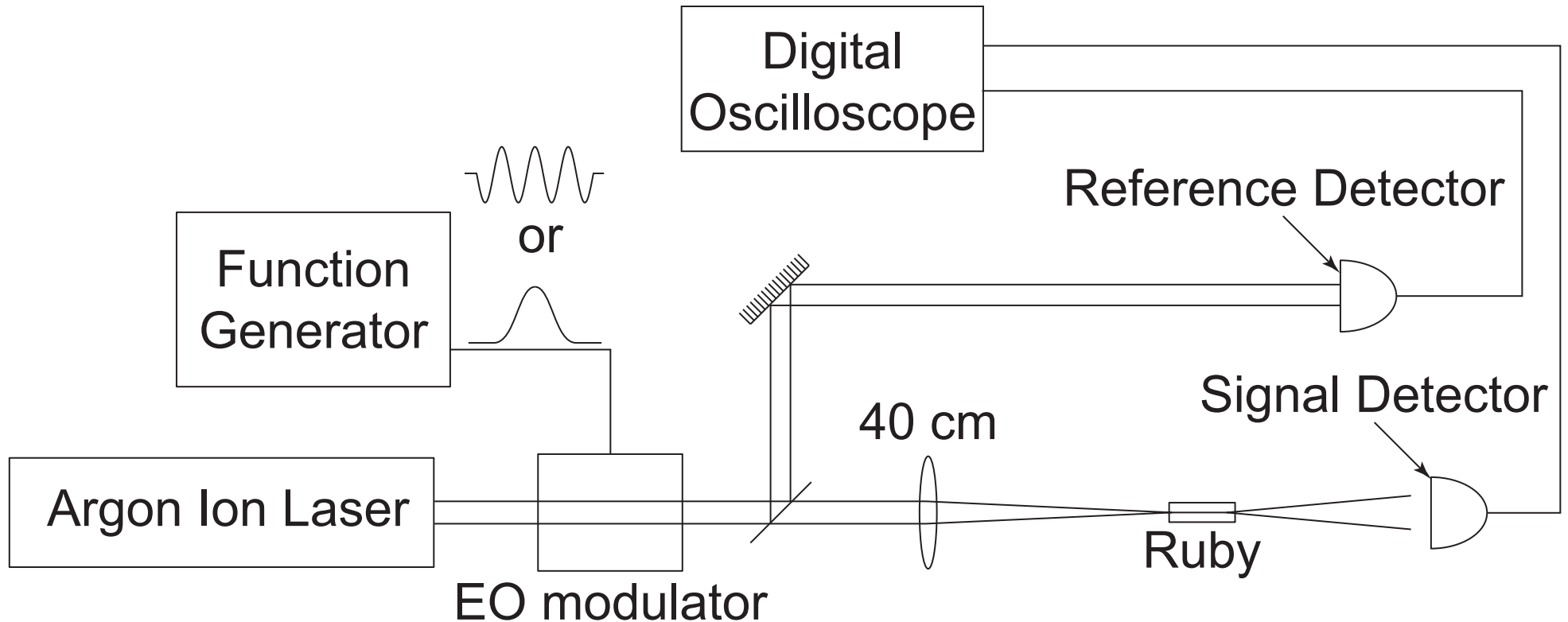


inhomogeneously
broadened medium



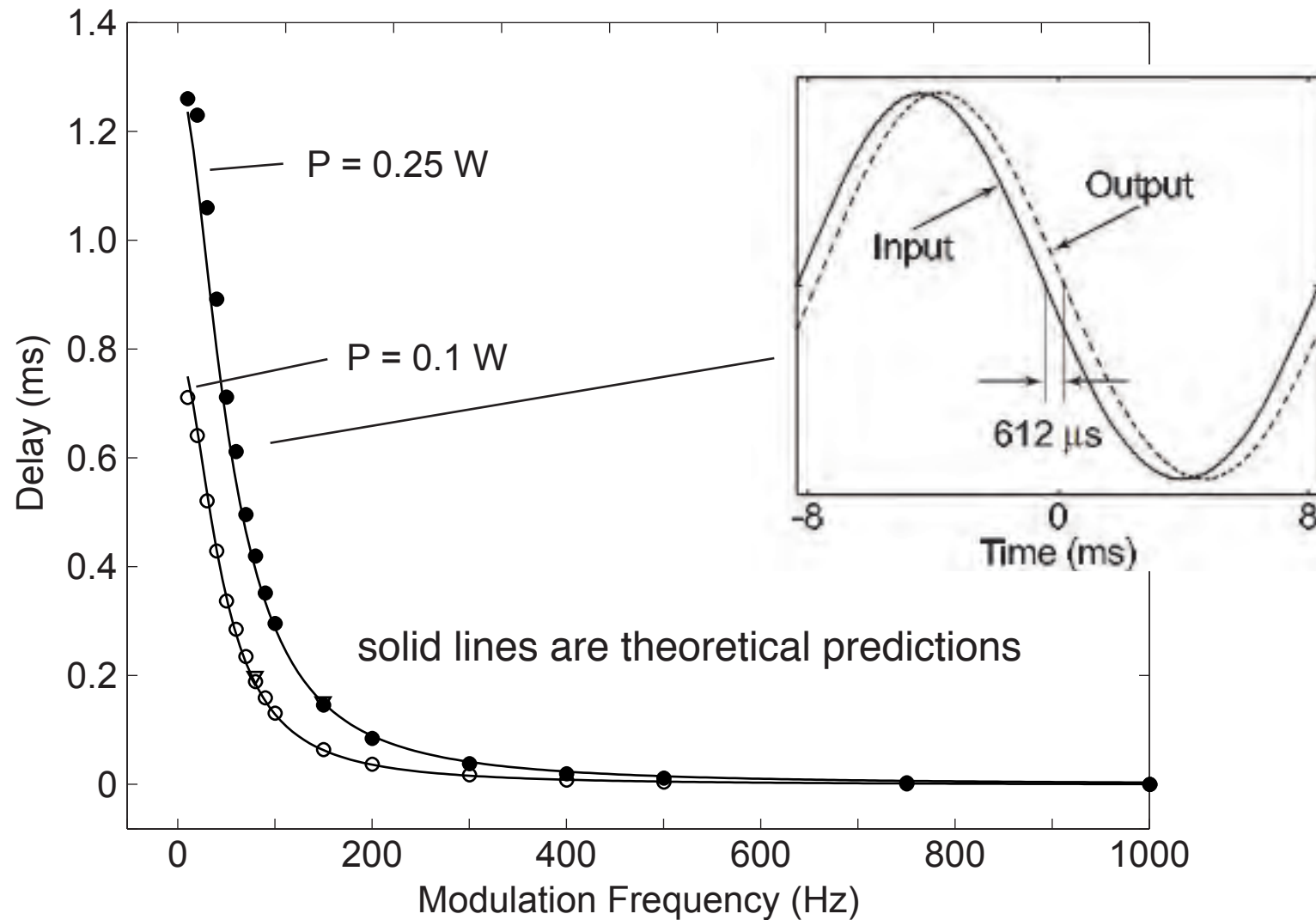
homogeneously
broadened medium
(or inhomogeneously
broadened)

Slow Light Experimental Setup



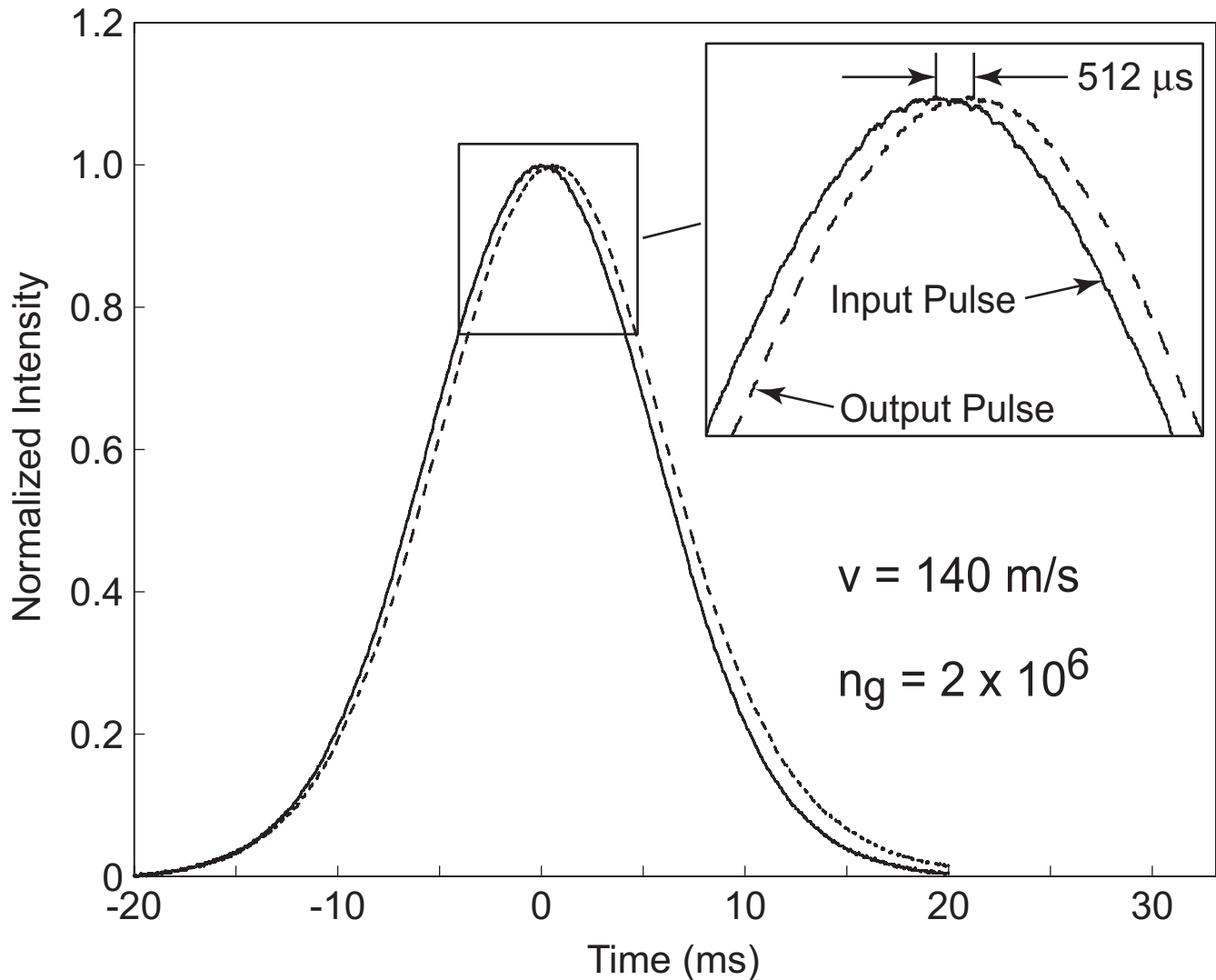
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



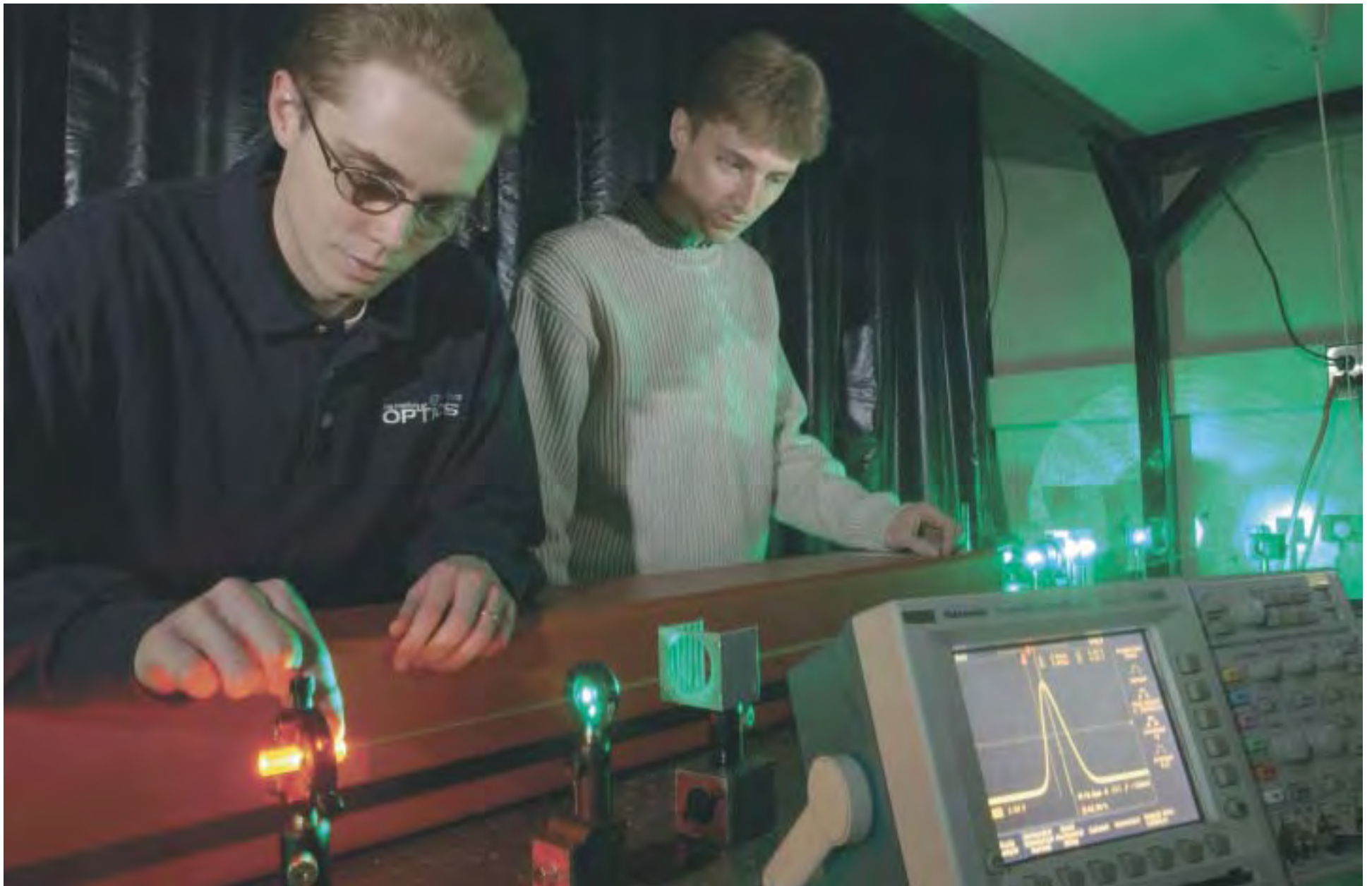
For 1.2 ms delay, $v = 60 \text{ m/s}$ and $n_g = 5 \times 10^6$

Gaussian Pulse Propagation Through Ruby



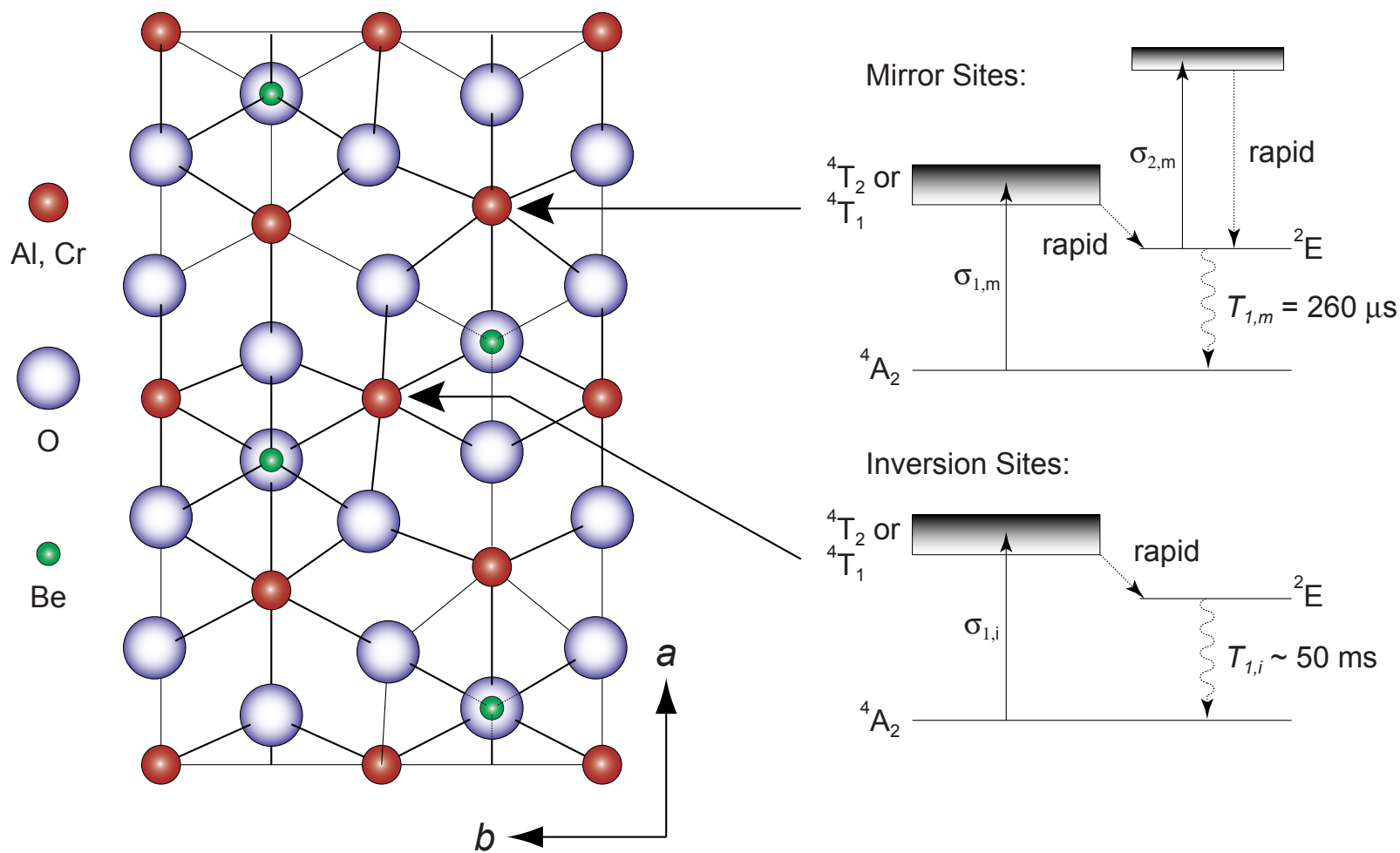
No pulse distortion!

Matt Bigelow and Nick Lepeshkin in the Lab



Alexandrite Displays both Saturable and Reverse-Saturable Absorption

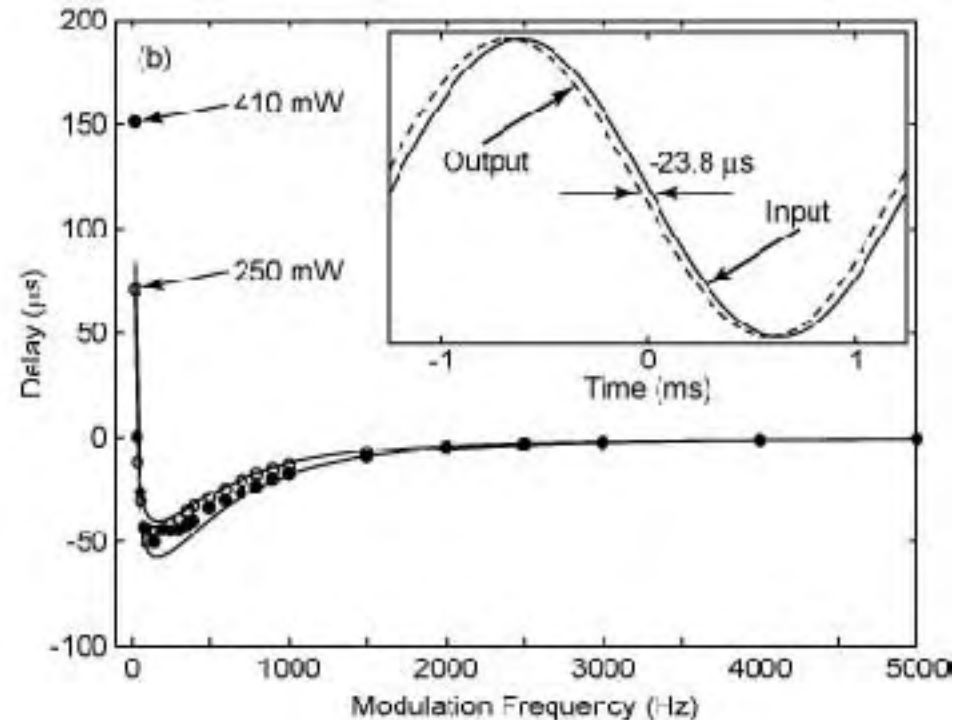
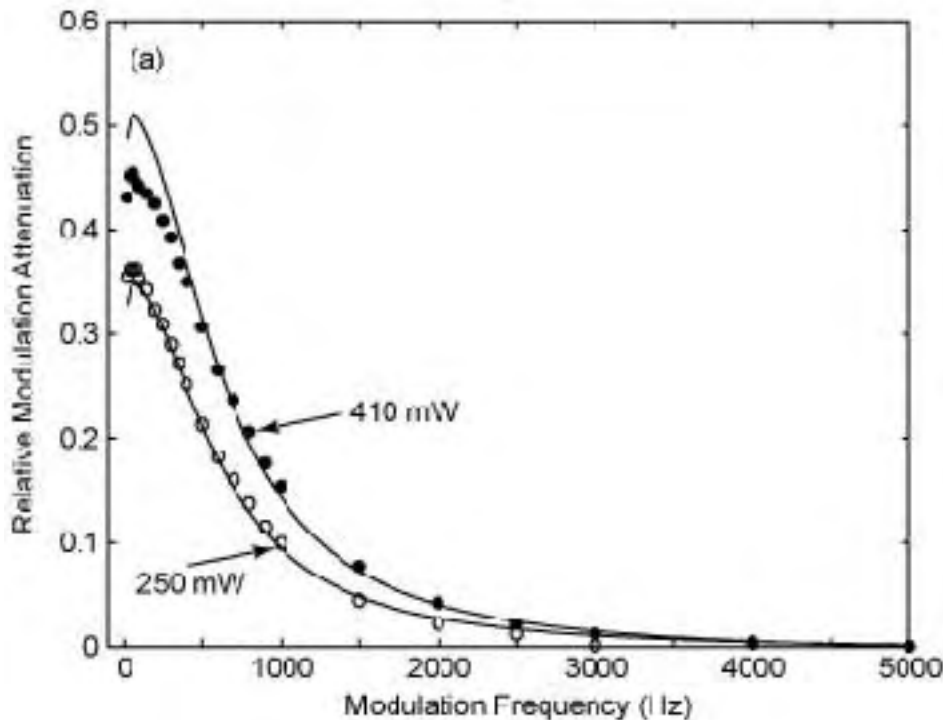
- Both slow and fast propagation observed in alexandrite



Inverse-Saturable Absorption Produces Superluminal Propagation in Alexandrite

At 476 nm, alexandrite is an inverse saturable absorber

Negative time delay of 50 μs corresponds 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 reduced 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.

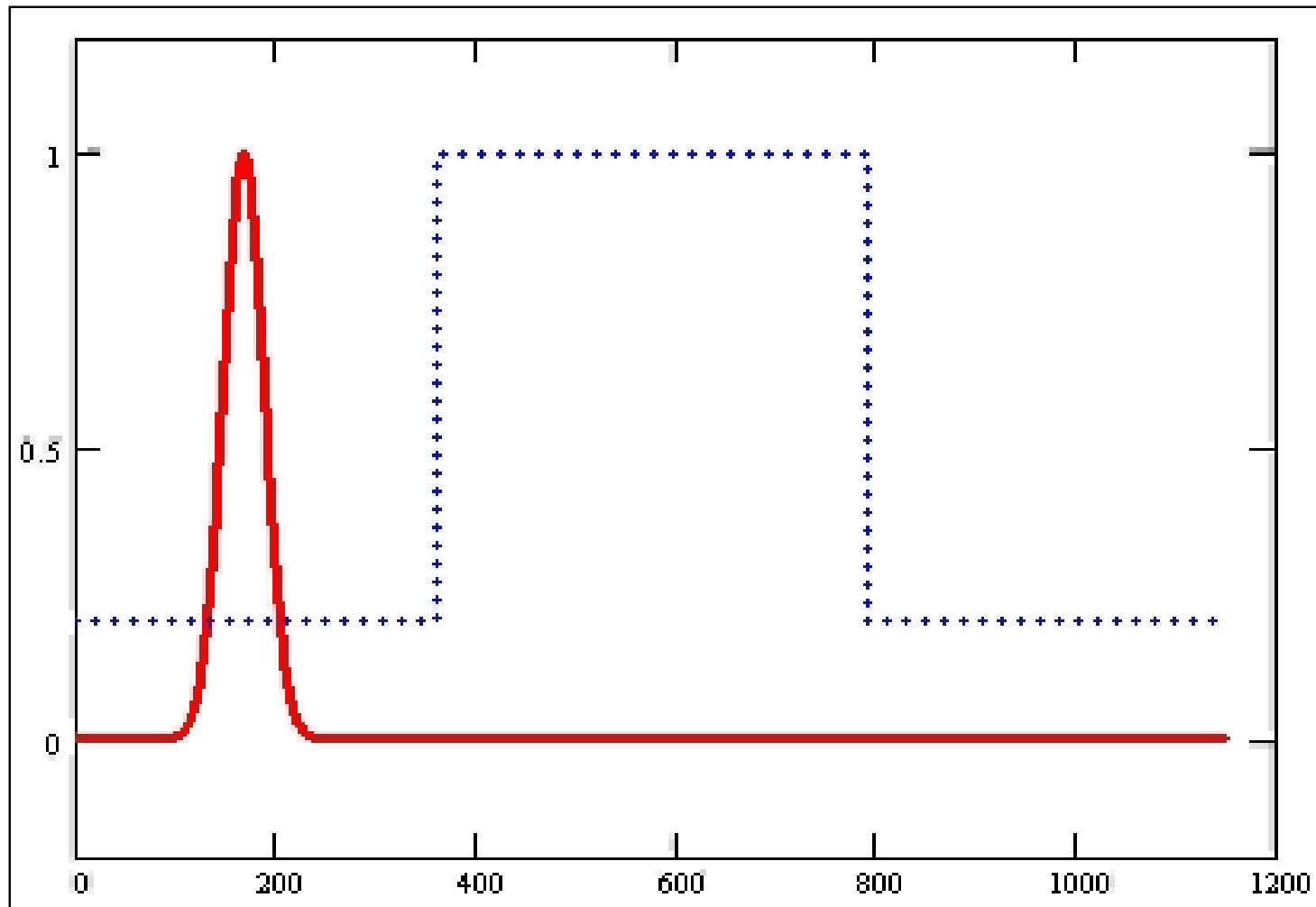
Study three cases:

Slow light $v_g = 0.5 c$

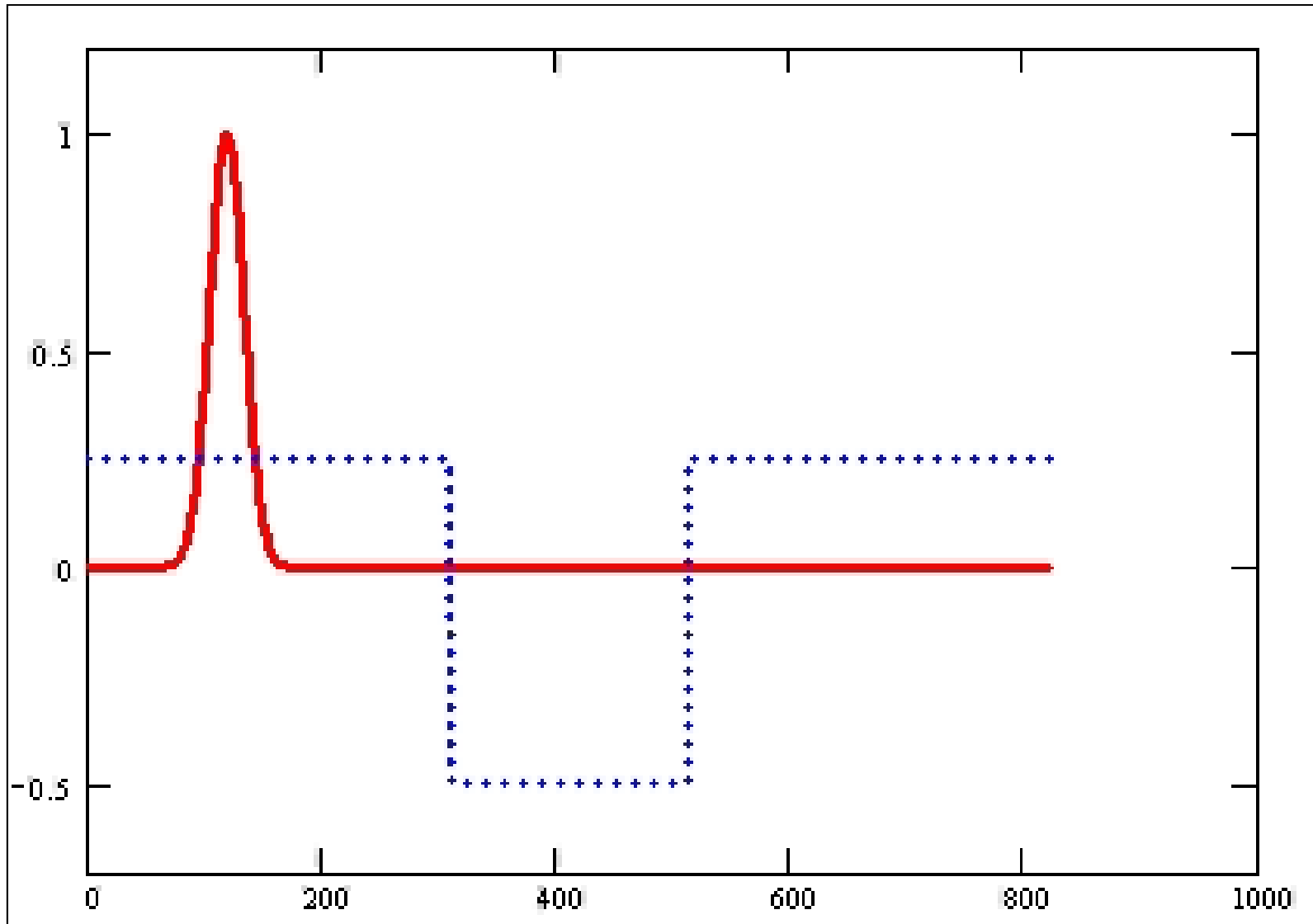
Fast light $v_g = 5 c$ and $v_g = -2 c$

CAUTION: This is a very simplistic model. It ignores GVD and spectral reshaping.

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

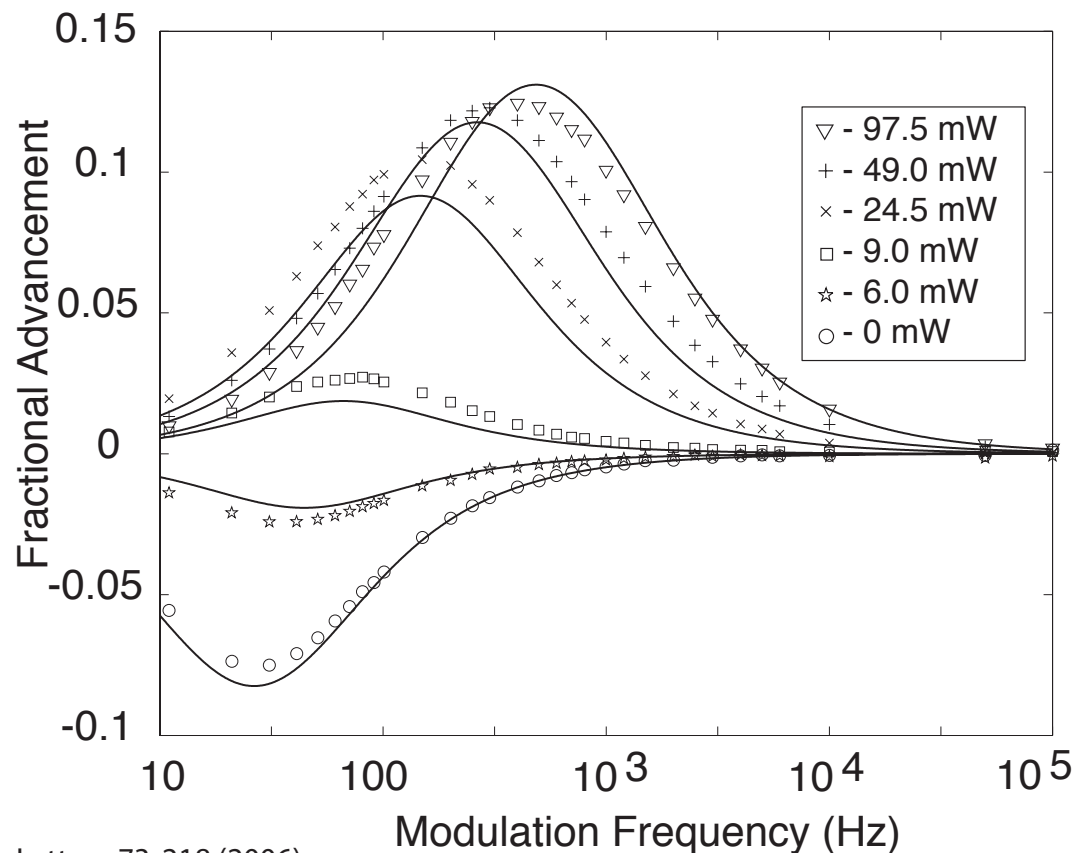
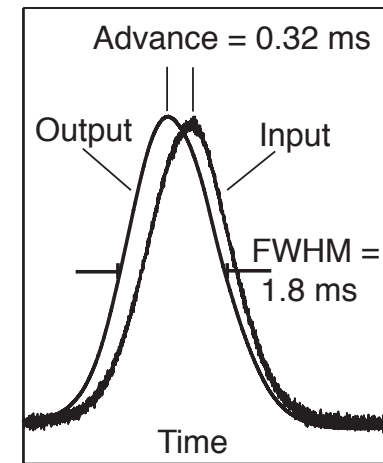
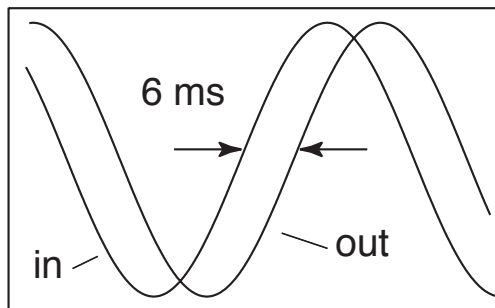
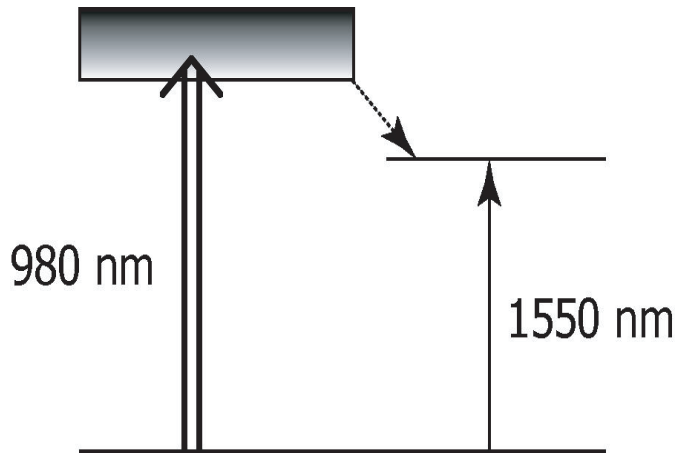


Pulse Propagation through a Backwards-Light Medium ($n_g = -.5$, $v_g = -2 c$)

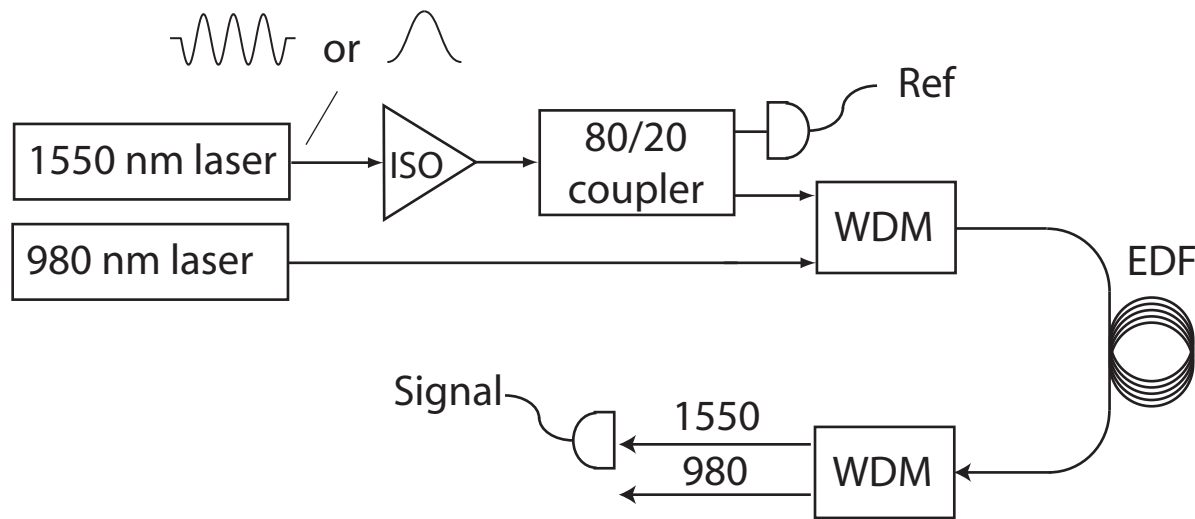


Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



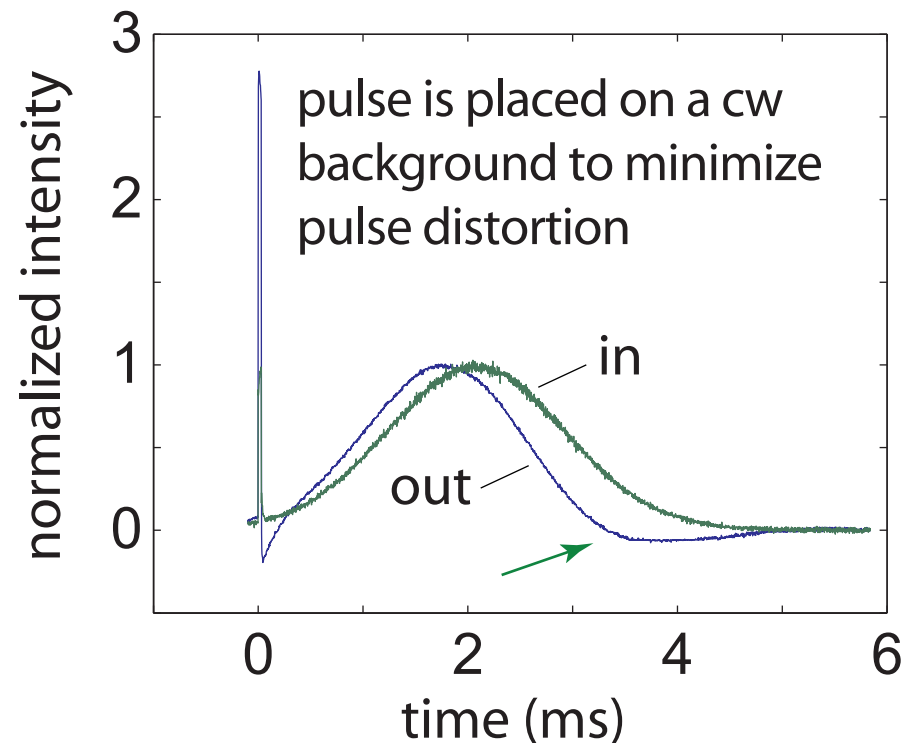
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



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

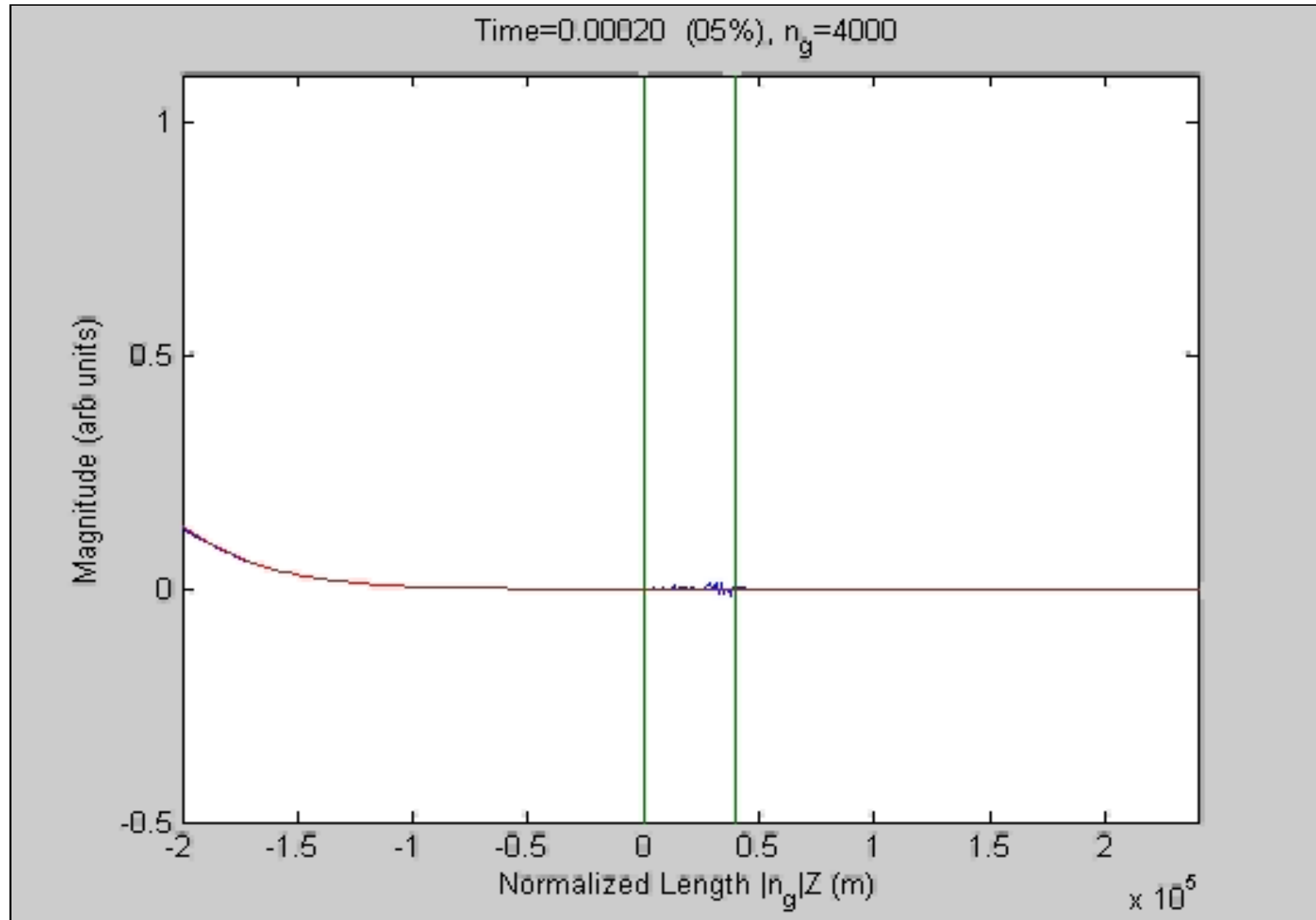
Procedure

- cutback method
- couplers embedded in fiber



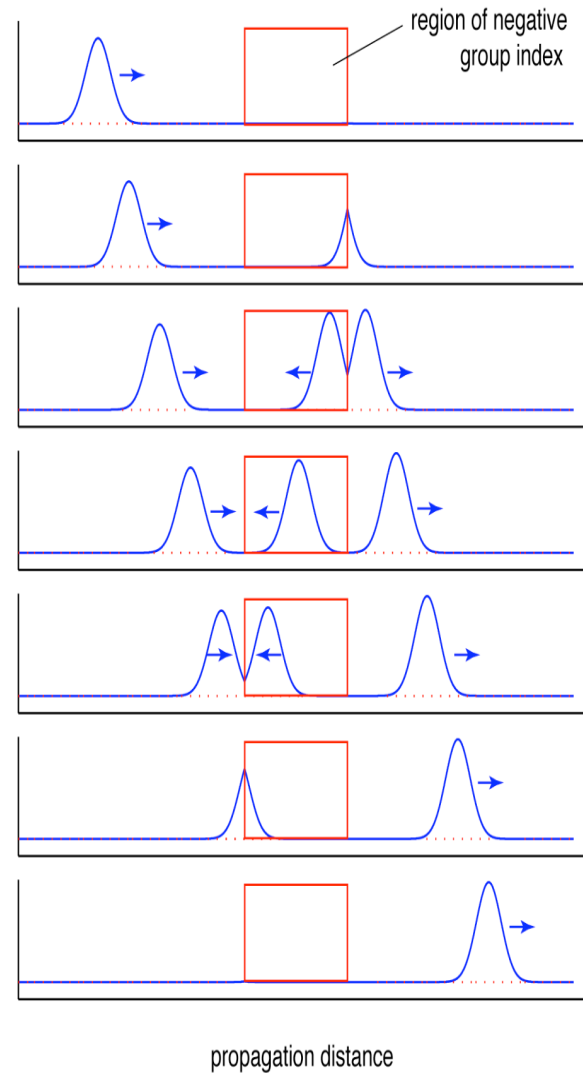
Experimental Results: Backward Propagation in Erbium-Doped Fiber

Normalized: (Amplification removed numerically)

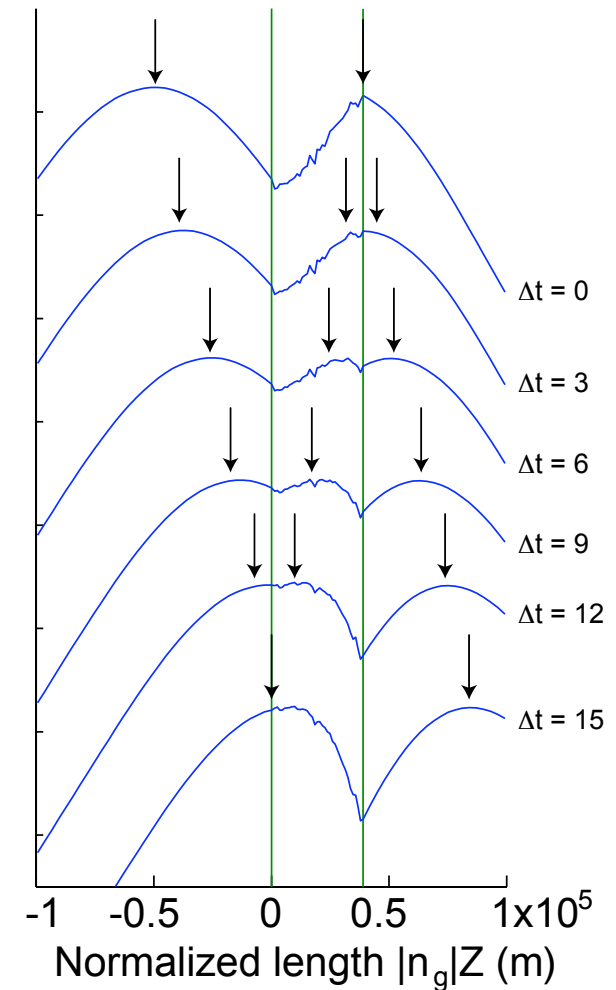


- A strongly counterintuitive phenomenon
- But entirely consistent with established physics
- G. M. Gehring, A. Schweinsberg, C. Barsi, N. Kostinski, and R. W. Boyd, *Science* 312, 985 2006.

- conceptual prediction



- laboratory results



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

Summary:

“Backwards” propagation is a realizable physical effect.

(Of course, many other workers have measured negative time delays. Our contribution was to measure the pulse evolution within the material medium.)

Causality and Superluminal Signal Transmission

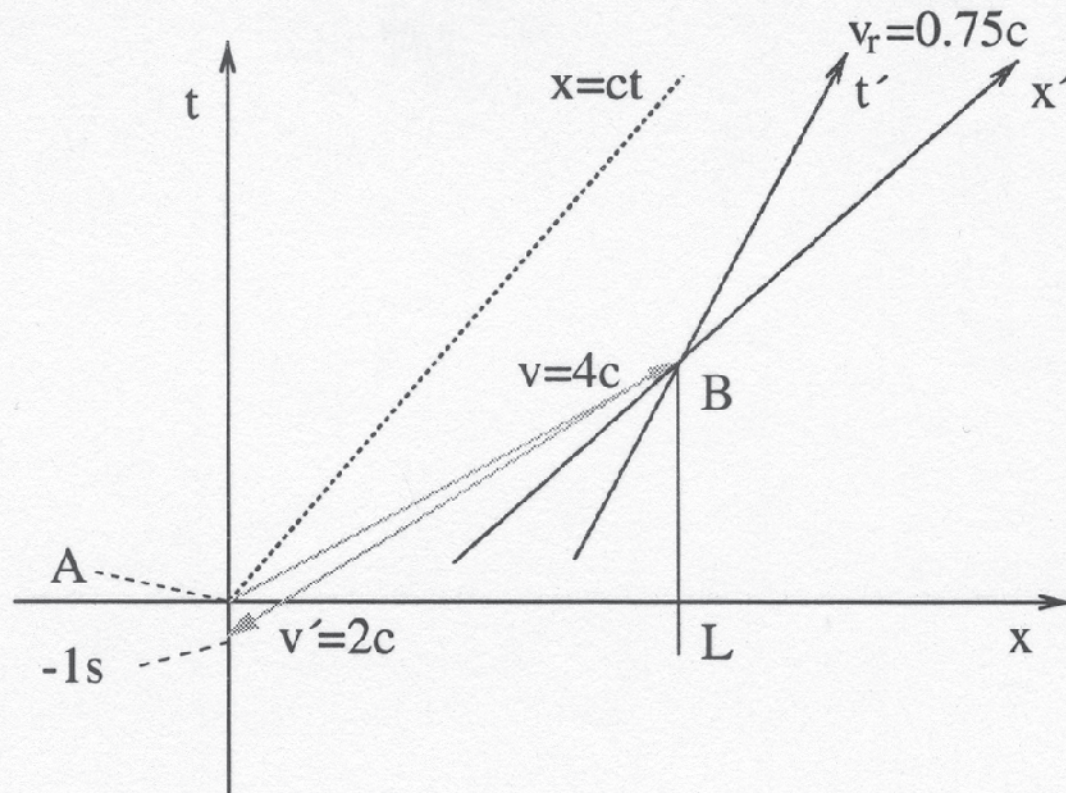
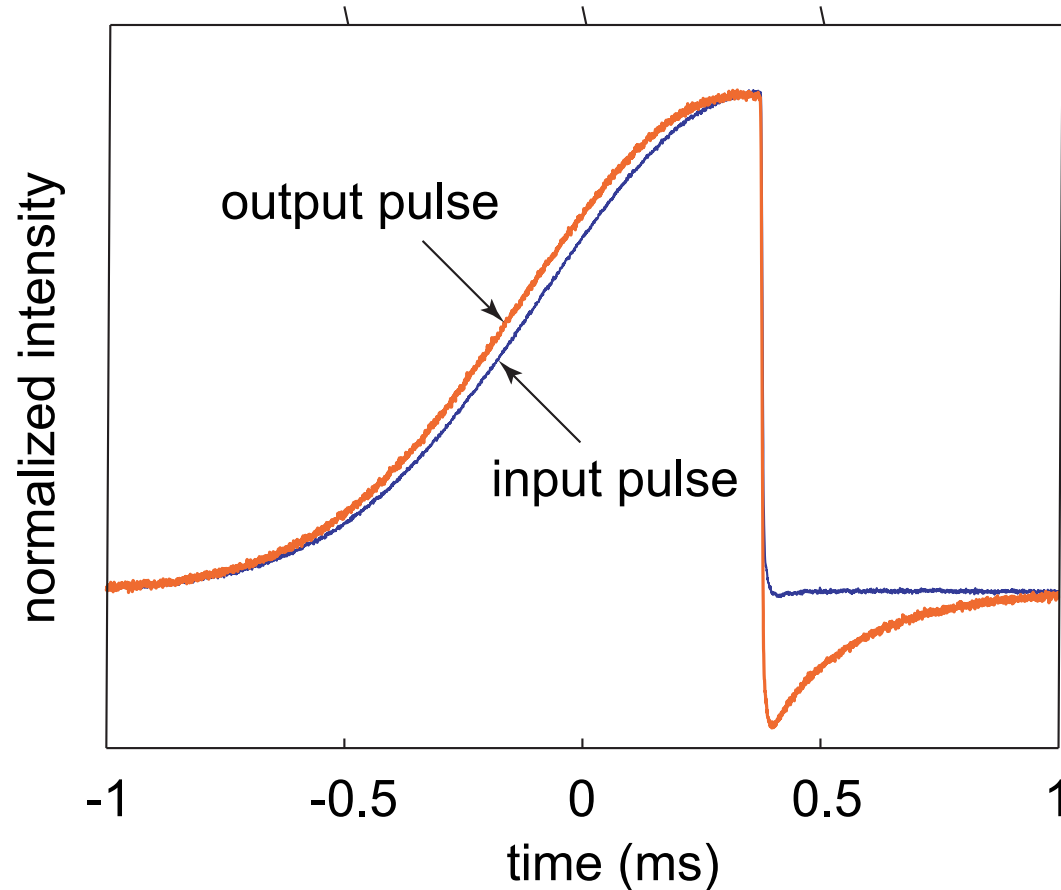


Fig. 6 Coordinates of two inertial observers **A** $(0,0)$ and **B** with $O(x,t)$ and $O'(x',t')$ moving with a relative velocity of $0.75c$. The distance L between **A** and **B** is 2000000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v'_s = 2c$. The numbers in the example are chosen arbitrarily. The signal returns -1 s in the past in **A**.

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

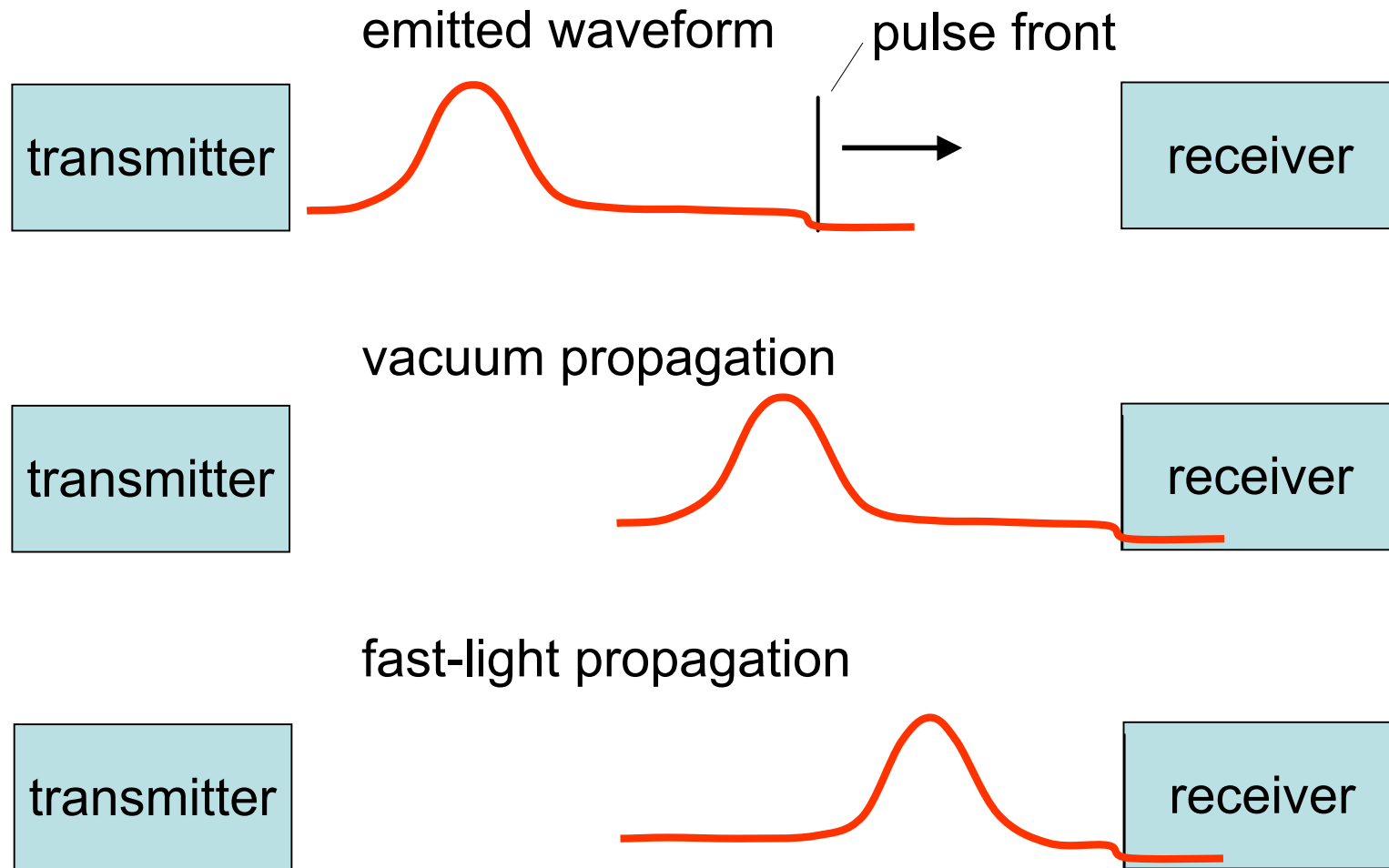


Smooth part of pulse propagates at group velocity
Discontinuity propagates at phase velocity
Information resides in points of discontinuity

Bigelow, Lepeshkin, Shin, and Boyd, *J. Phys: Condensed Matter*, 3117, 2006.

See also Stenner, Gauthier, and Neifeld, *Nature*, 425, 695, 2003.

How to Reconcile Superluminality with Causality



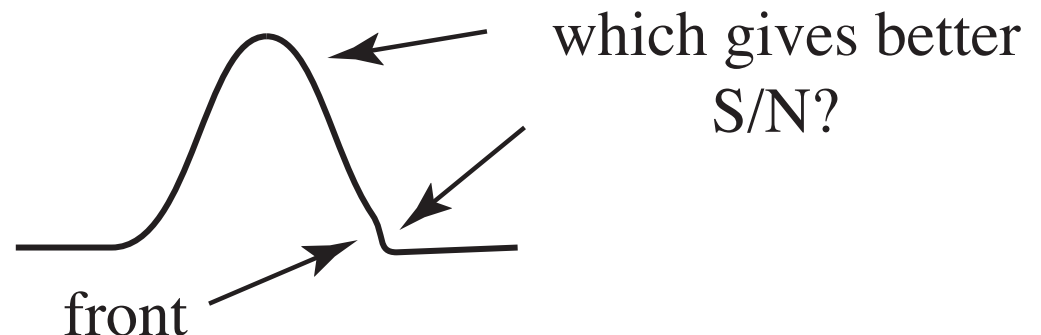
Information Velocity – Tentative Conclusions

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 measurements of the information content only near the peak of the pulse.

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

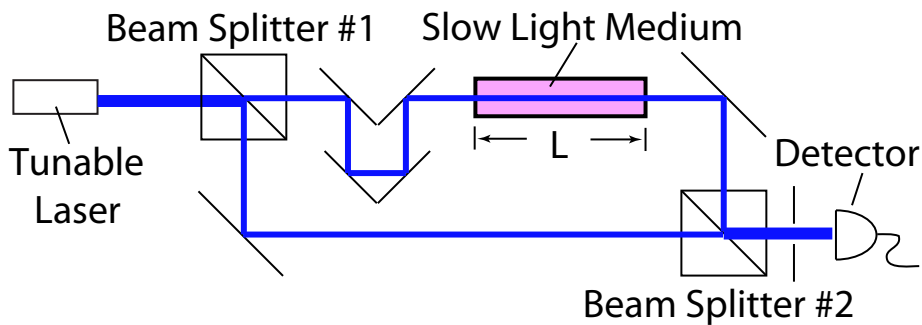
In a real communication system it would be really stupid to transmit pulses containing so much energy that one can reliably detect the very early leading edge of the pulse.



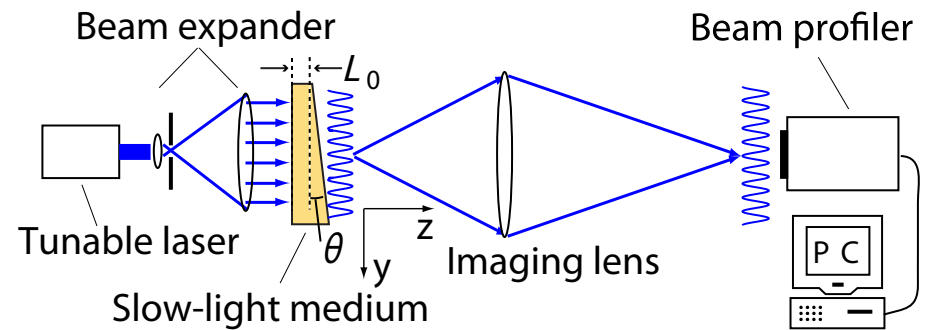
Interferometry and Slow Light

- Under certain (but not all) circumstances, the sensitivity of an interferometer is increased by the group index of the material within the interferometer!
- Sensitivity of a spectroscopic interferometer is increased

Typical interferometer:



We use $\text{CdS}_x\text{Se}_{1-x}$ as our slow-light medium

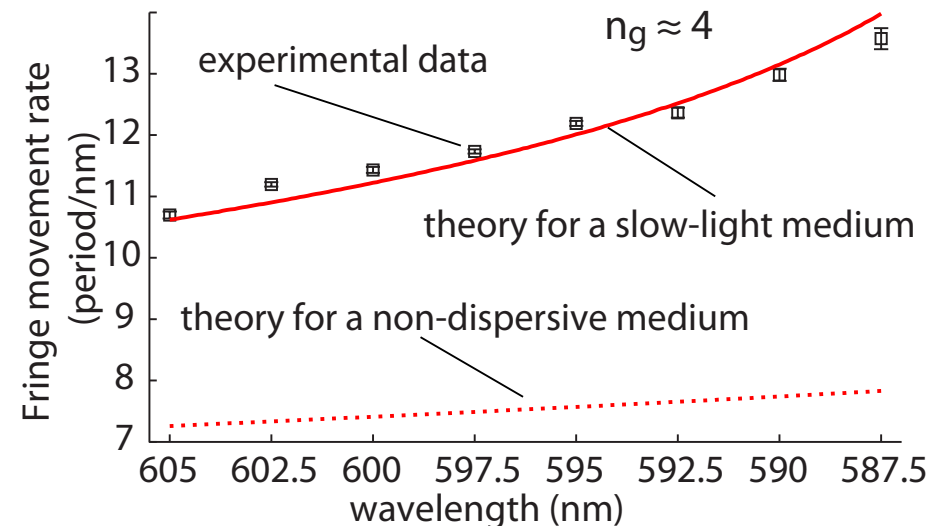


Here is why it works:

$$\frac{d\Delta\phi}{d\omega} = \frac{d}{d\omega} \left(\frac{\omega n L}{c} \right) = \frac{L}{c} \left(n + \omega \frac{dn}{d\omega} \right) = \frac{L n_g}{c}$$

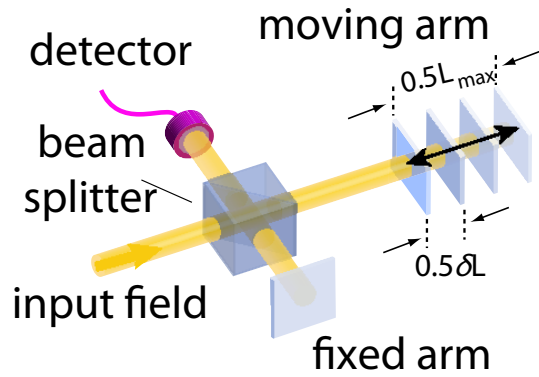
Shih et al, Opt. Lett. 2007

Our experimental results

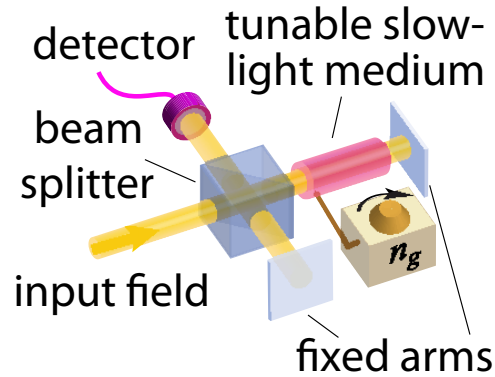


High-Resolution Slow-Light Fourier Transform Interferometer

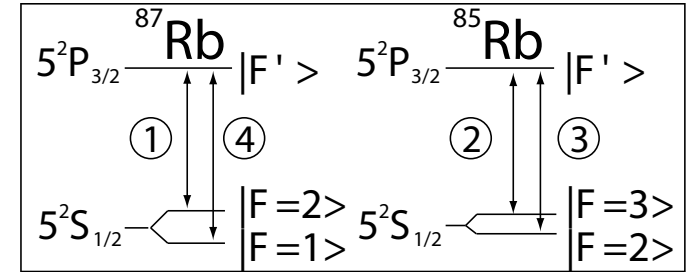
Conventional FT Interferometer



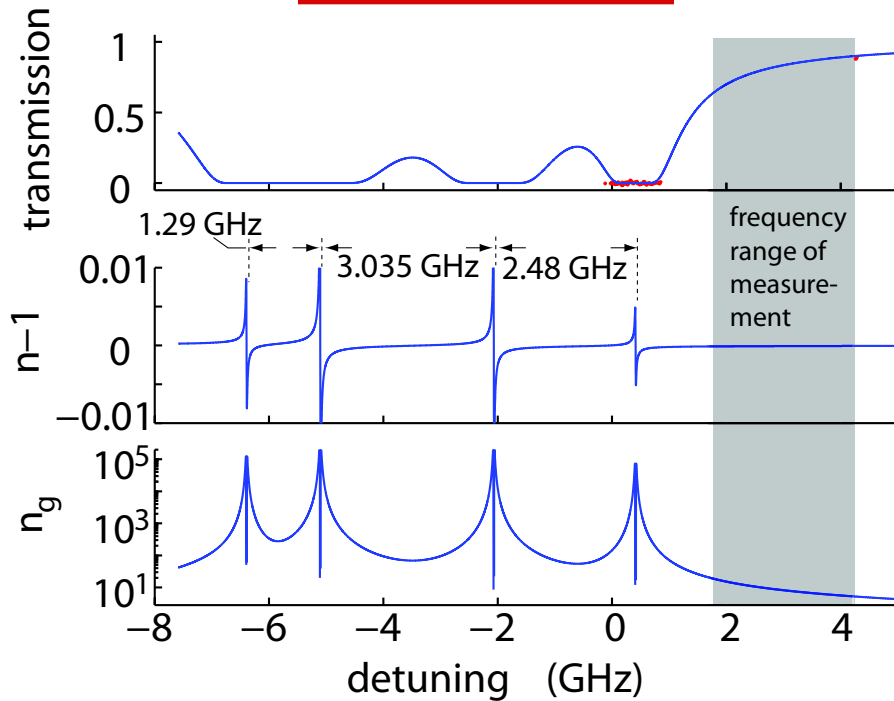
Slow-light FT Interferometer



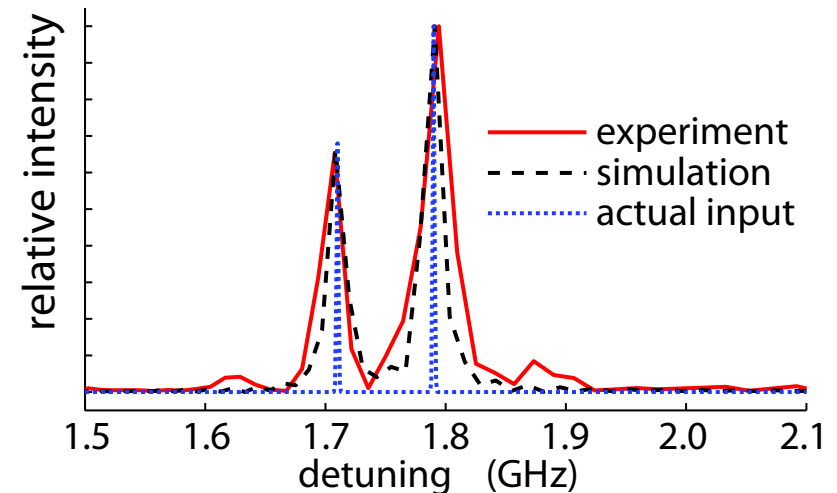
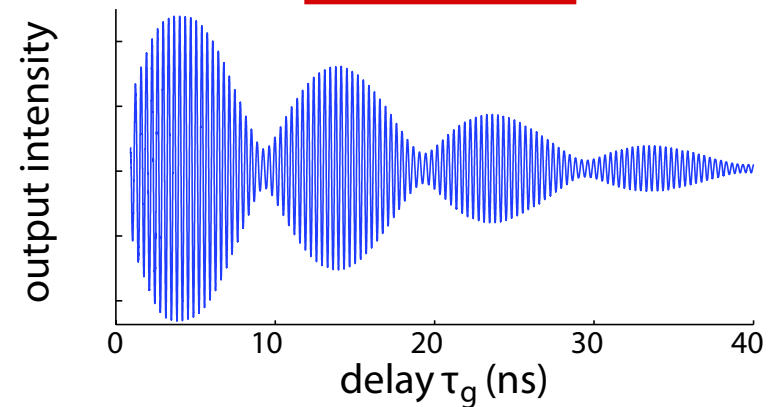
Energy Levels



Theoretical Model

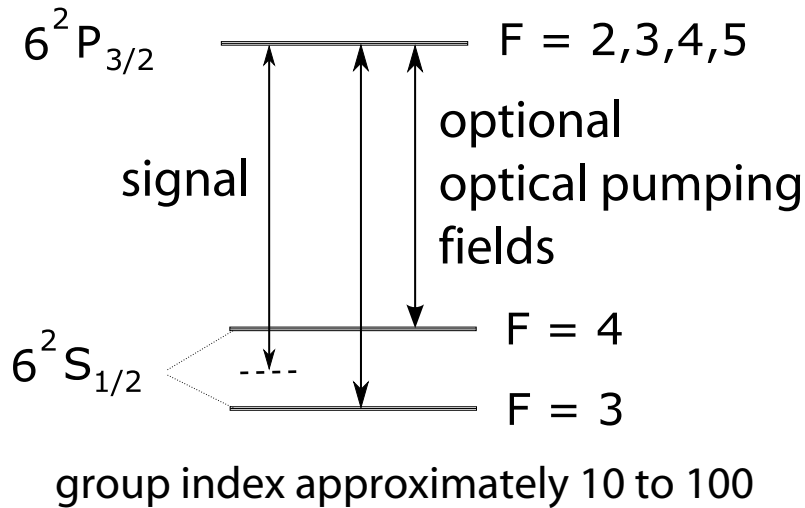


Results

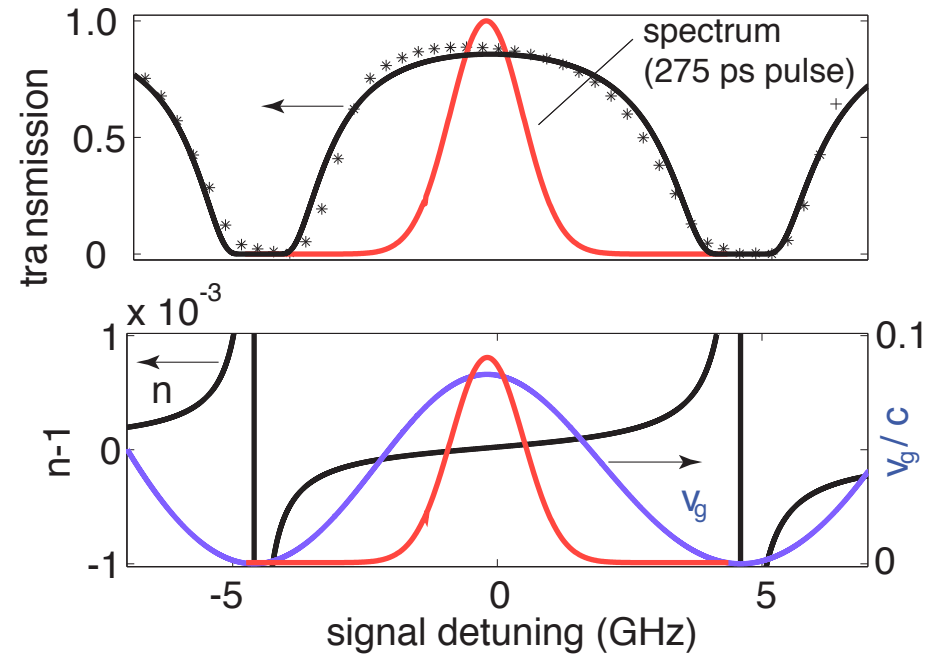
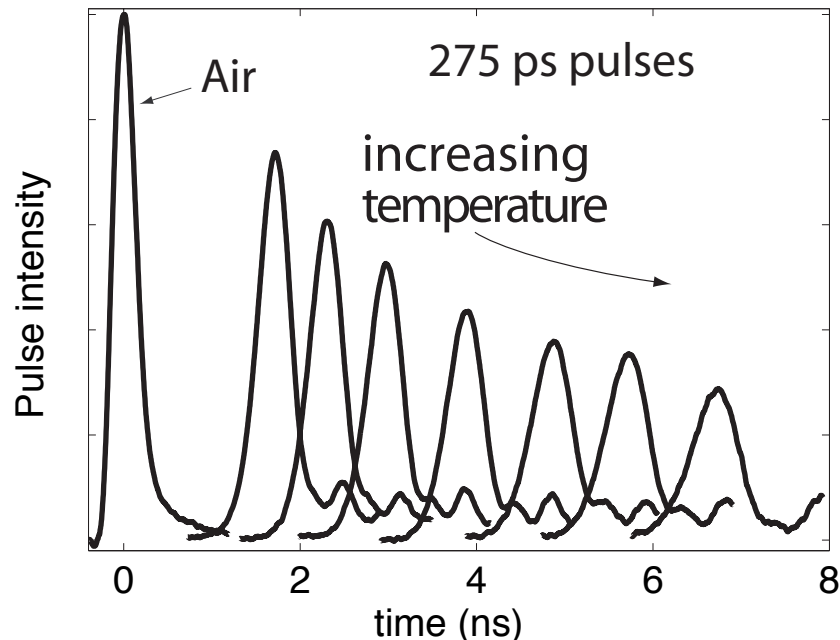


Tunable Delays of up to 80 Pulse Widths in Atomic Cesium Vapor

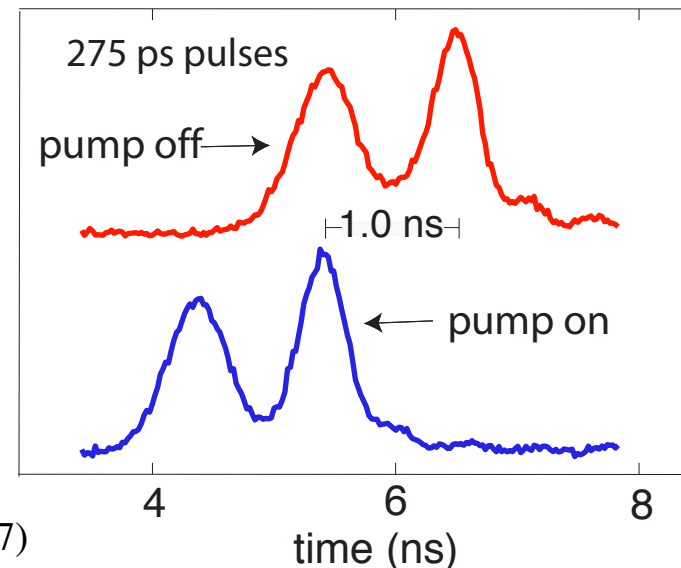
There is no delay-bandwidth product limitation on slow light!



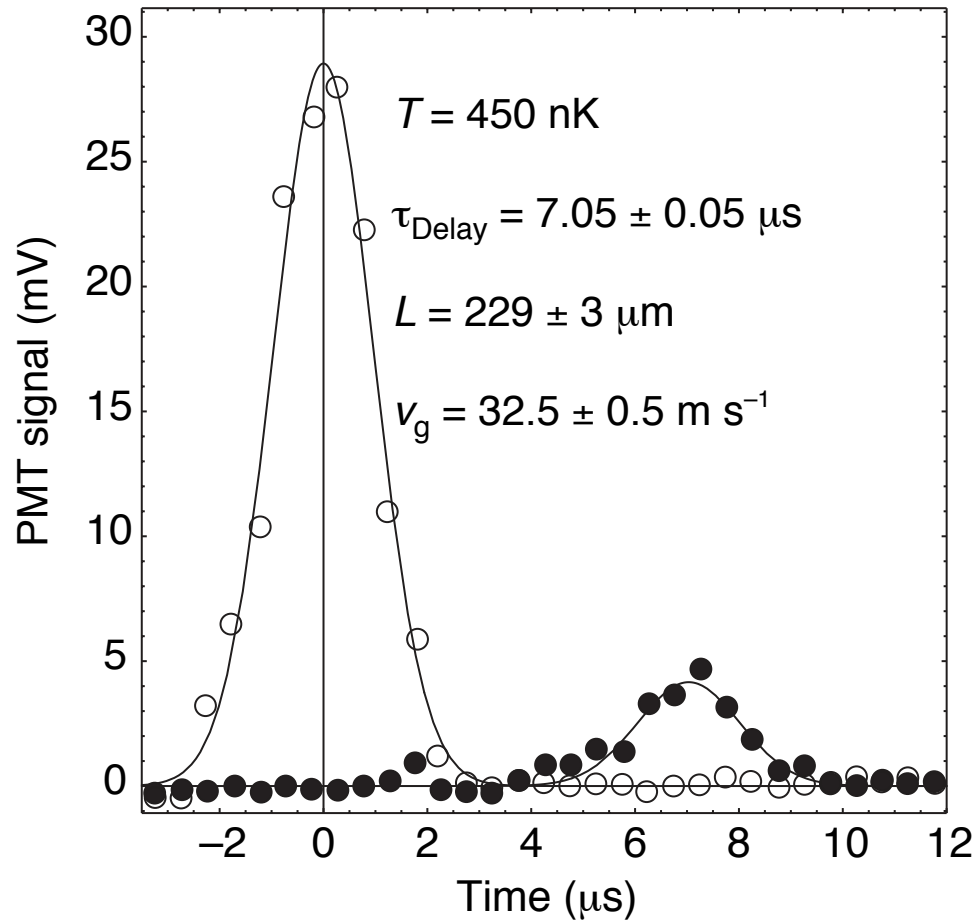
- coarse tuning: temperature



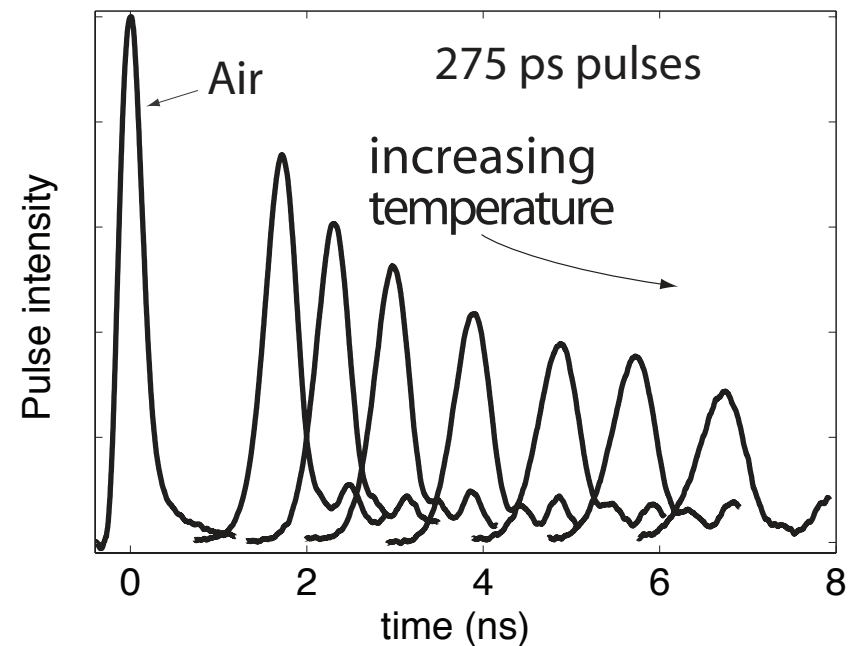
- fine tuning: optical pumping



Summary – Progress in Slow-Light Research



Delay of 3 pulse widths (1999)
Results of Hau, L

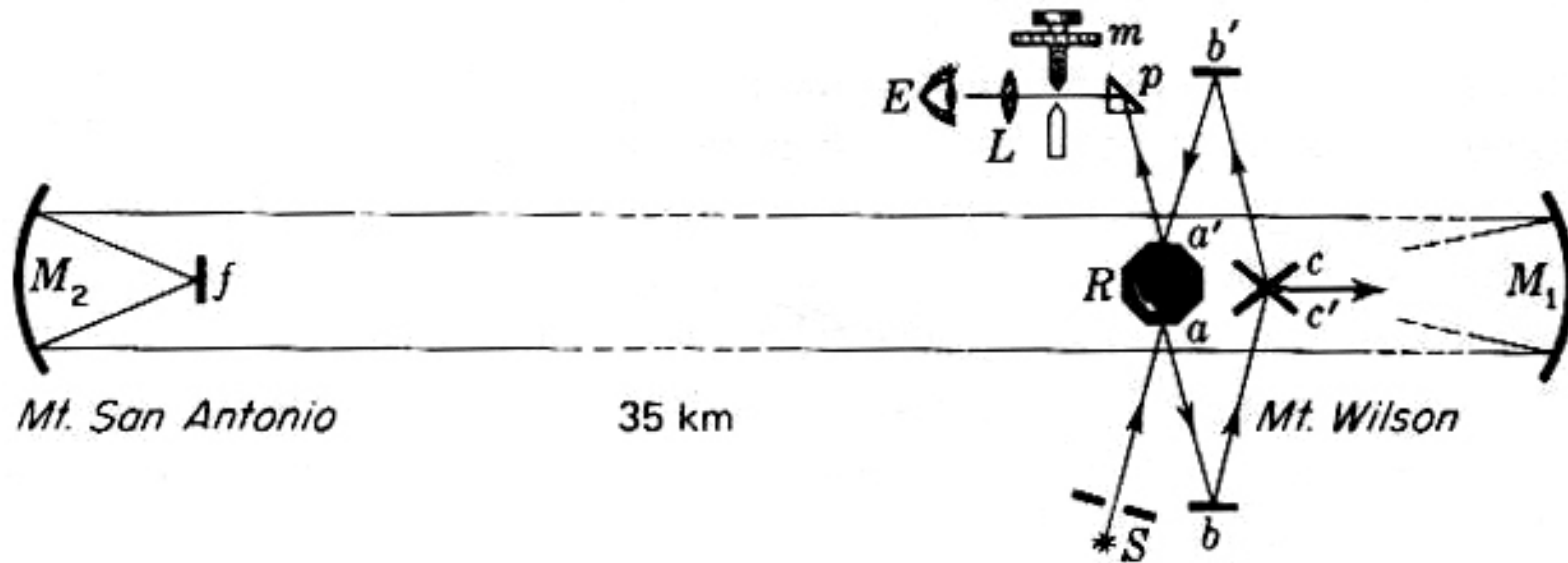


Delay of 80 pulse widths (2007)
Results of Howell

Historical Summary

Measurements of the Velocity of Light

Michelson (1926); Improved time of flight method.



Rotating octagonal mirror

$$c = 299,796 \text{ km/s (or } 299,798 \text{ km/s)}$$

Determination of the Velocity of Light Laboratory Methods

VOLUME 29, NUMBER 19

PHYSICAL REVIEW LETTERS

6 NOVEMBER 1972

Speed of Light from Direct Frequency and Wavelength Measurements of the Methane-Stabilized Laser

K. M. Evenson, J. S. Wells, F. R. Petersen, B. L. Danielson, and G. W. Day
Quantum Electronics Division, National Bureau of Standards, Boulder, Colorado 80302

and

R. L. Barger* and J. L. Hall†
National Bureau of Standards, Boulder, Colorado 80302
(Received 11 September 1972)

The frequency and wavelength of the methane-stabilized laser at $3.39 \mu\text{m}$ were directly measured against the respective primary standards. With infrared frequency synthesis techniques, we obtain $\nu = 88.376\,181\,627(50)$ THz. With frequency-controlled interferometry, we find $\lambda = 3.392\,231\,376(12) \mu\text{m}$. Multiplication yields the speed of light $c = 299\,792\,456.2(1.1)$ m/sec, in agreement with and 100 times less uncertain than the previously accepted value. The main limitation is asymmetry in the krypton $6057\text{-}\text{\AA}$ line defining the meter.

$c = 299\,792\,458$

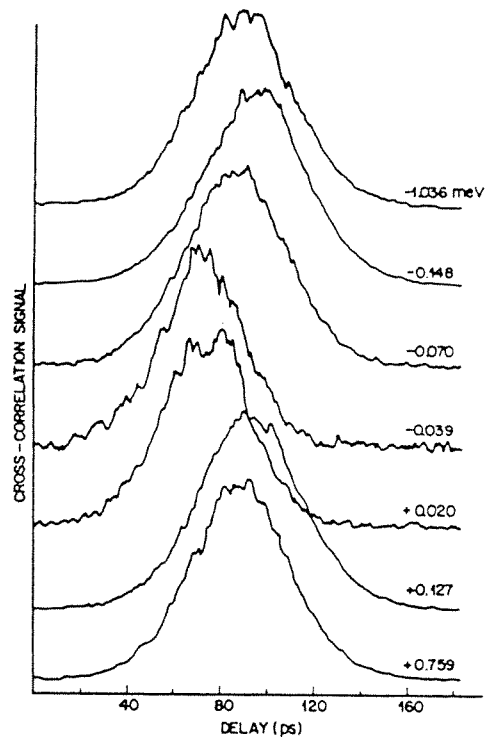
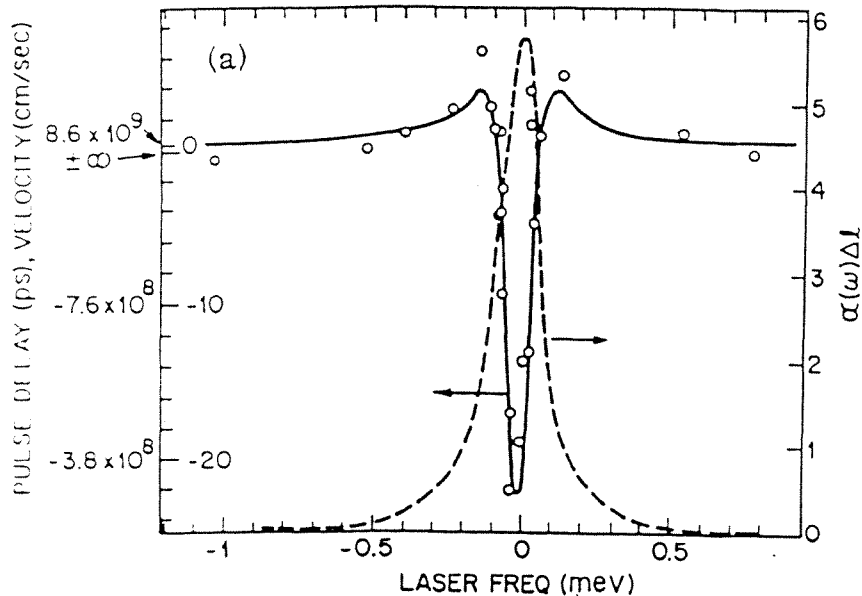
Linear Pulse Propagation in an Absorbing Medium

S. Chu and S. Wong

Bell Laboratories, Murray Hill, New Jersey 07974

(Received 30 November 1981)

The pulse velocity in the linear regime in samples of GaP:N with a laser tuned to the bound A-exciton line is measured with use of a picosecond time-of-flight technique. The pulse is seen to propagate through the material with little pulse-shape distortion, and with an envelope velocity given by the group velocity even when the group velocity exceeds 3×10^{10} cm/sec, equals $\pm \infty$, or becomes negative. The results verify the predictions of Garrett and McCumber.



Amplification of Light and Atoms in a Bose-Einstein Condensate

S. Inouye, R. F. Löw, S. Gupta, T. Pfau, A. Görlitz, T. L. Gustavson, D. E. Pritchard, and W. Ketterle

*Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139*

(Received 27 June 2000)

A Bose-Einstein condensate illuminated by a single off-resonant laser beam (“dressed condensate”) shows a high gain for matter waves and light. We have characterized the optical and atom-optical properties of the dressed condensate by injecting light or atoms, illuminating the key role of long-lived matter wave gratings produced by the condensate at rest and recoiling atoms. The narrow bandwidth for optical gain gave rise to an extremely slow group velocity of an amplified light pulse (~ 1 m/s).

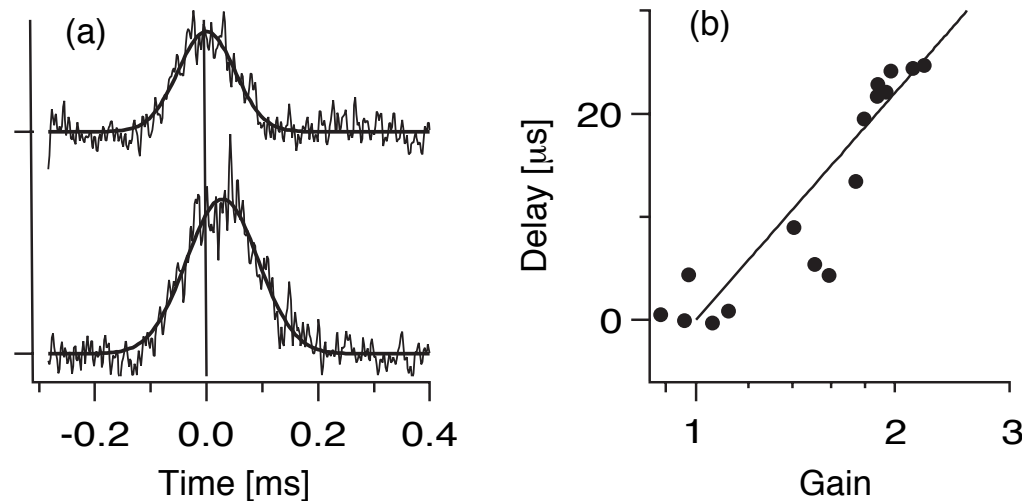


FIG. 3. Pulse delay due to light amplification. (a) About 20 ms delay was observed when a Gaussian pulse of about 140 ms width and 0.11 mW/cm^2 peak intensity was sent through the dressed condensate (bottom trace). The top trace is a reference taken without the dressed condensate. Solid curves are Gaussian fits to guide the eyes. (b) The observed delay t_D was proportional to $(\ln g)$, where g is the observed gain.

Aloha!



And thank you for your attention.

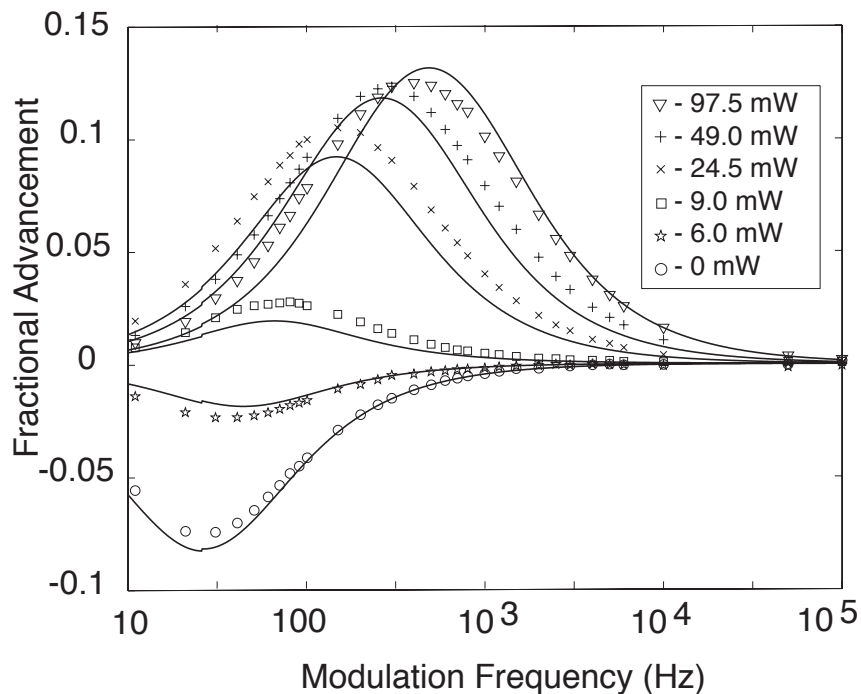
Special Thanks to My Students and Research Associates



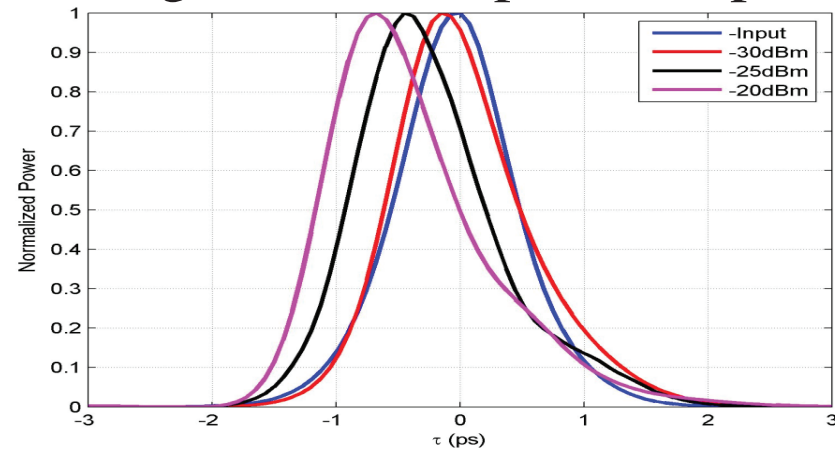
Slow Light via Coherent Population Oscillations

- Ultra-slow light ($n_g > 10^6$) observed in ruby and ultra-fast light ($n_g = -4 \times 10^5$) observed in alexandrite at room temperature.

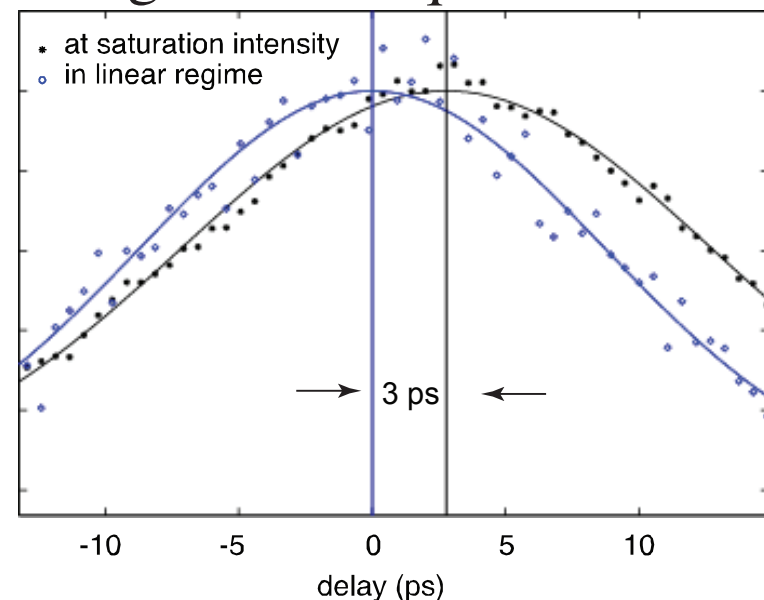
- Slow and fast light in an EDFA



- Slow light in a SC optical amplifier



- Slow light in PbS quantum dots



Thank you for your attention!

