# Slow, Fast, and “Backwards” Light

Robert W. Boyd

Institute of Optics and
Department of Physics and Astronomy
University of Rochester

http://www.optics.rochester.edu/~boyd

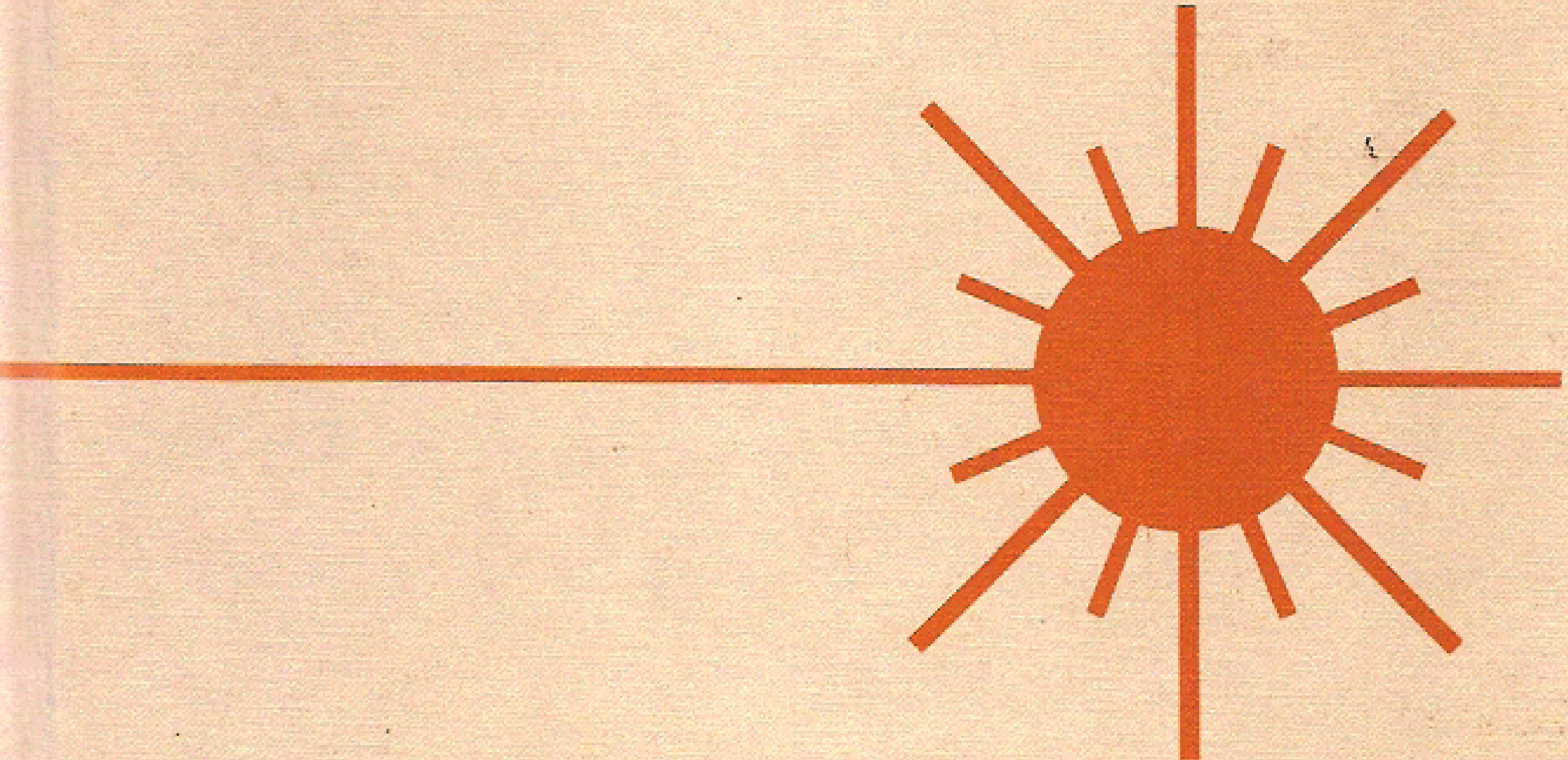
Loronzo M. Narducci Memorial Symposium, Drexel University, May 24-25, 2007.

Cambridge Studies in Modern Optics **4**

# Optical Instabilities

Edited by

R.W. BOYD, M.G. RAYMER, L.M. NARDUCCI



# Interest in Slow Light

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

Fundamentals of optical physics

Optical delay lines, optical storage, optical memories

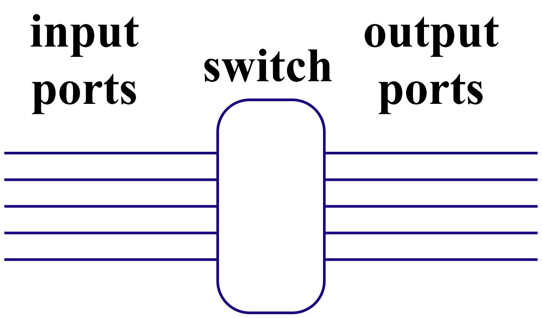
Implications for quantum information

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

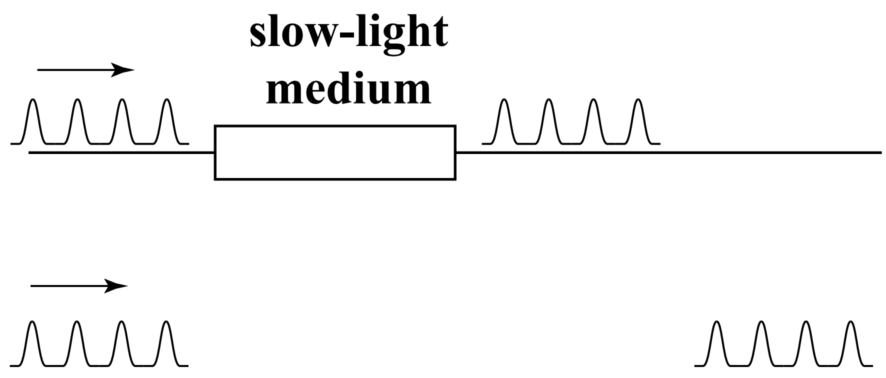
Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.

# Slow Light and Optical Buffers

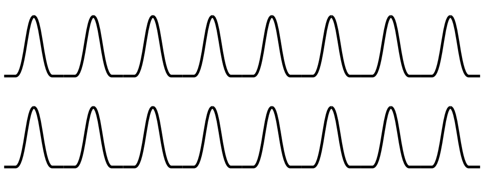
## All-Optical Switch




## 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.**


*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*

# Some Approaches to Slow Light Propagation

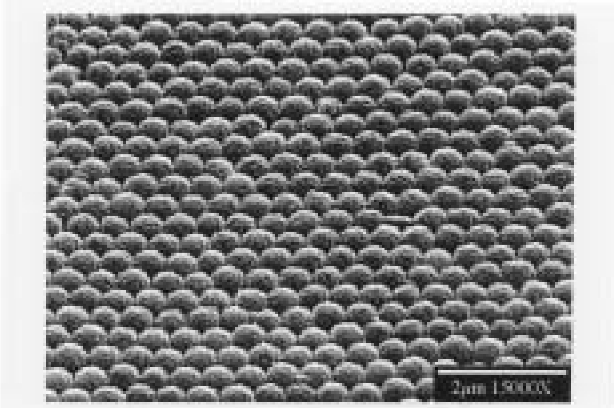
- Use the linear response of atomic systems

  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

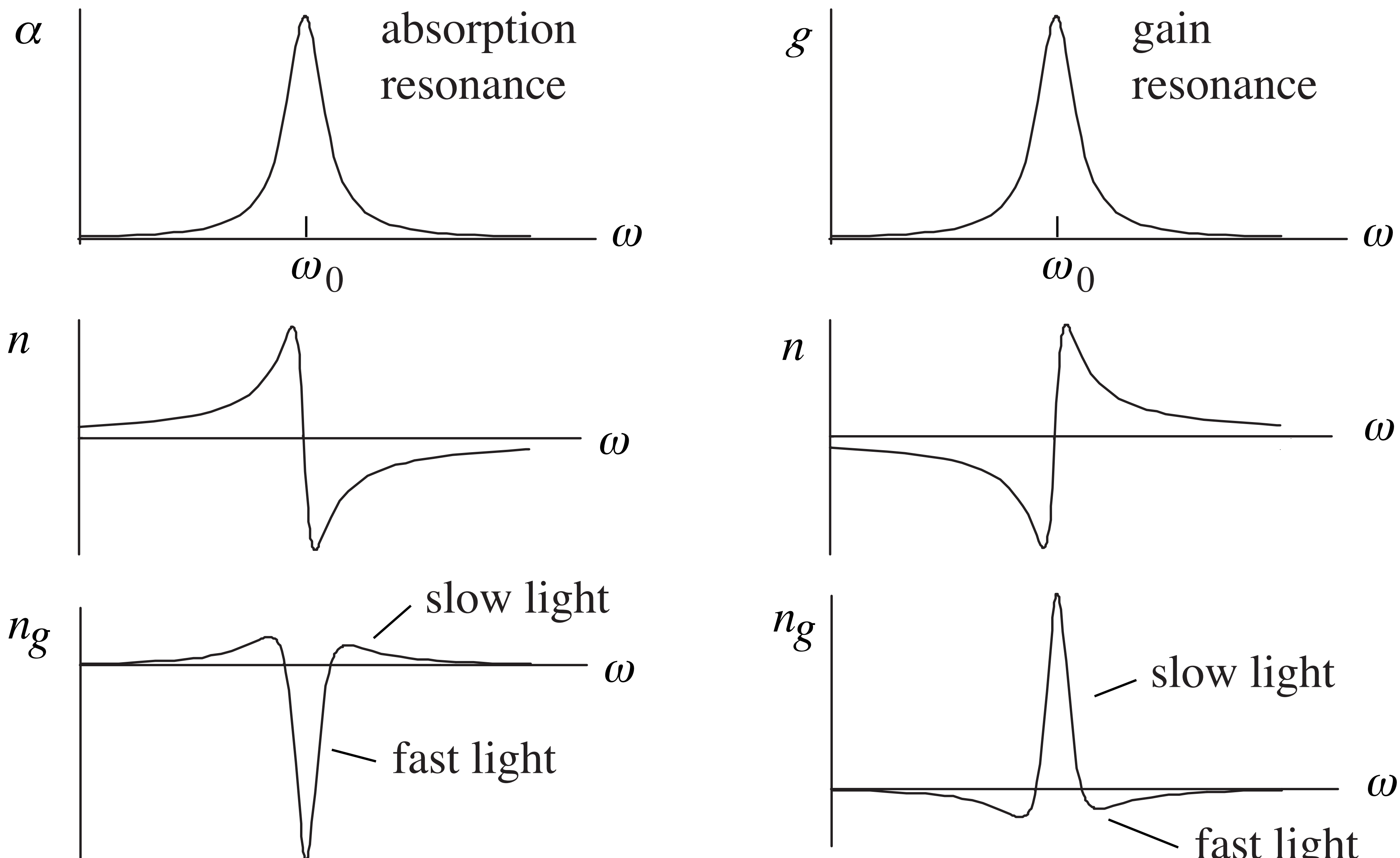
$$v_g = \frac{c}{n_g} \qquad n_g = n + \omega \frac{dn}{d\omega}$$

Want large dispersion to obtain extreme group velocities

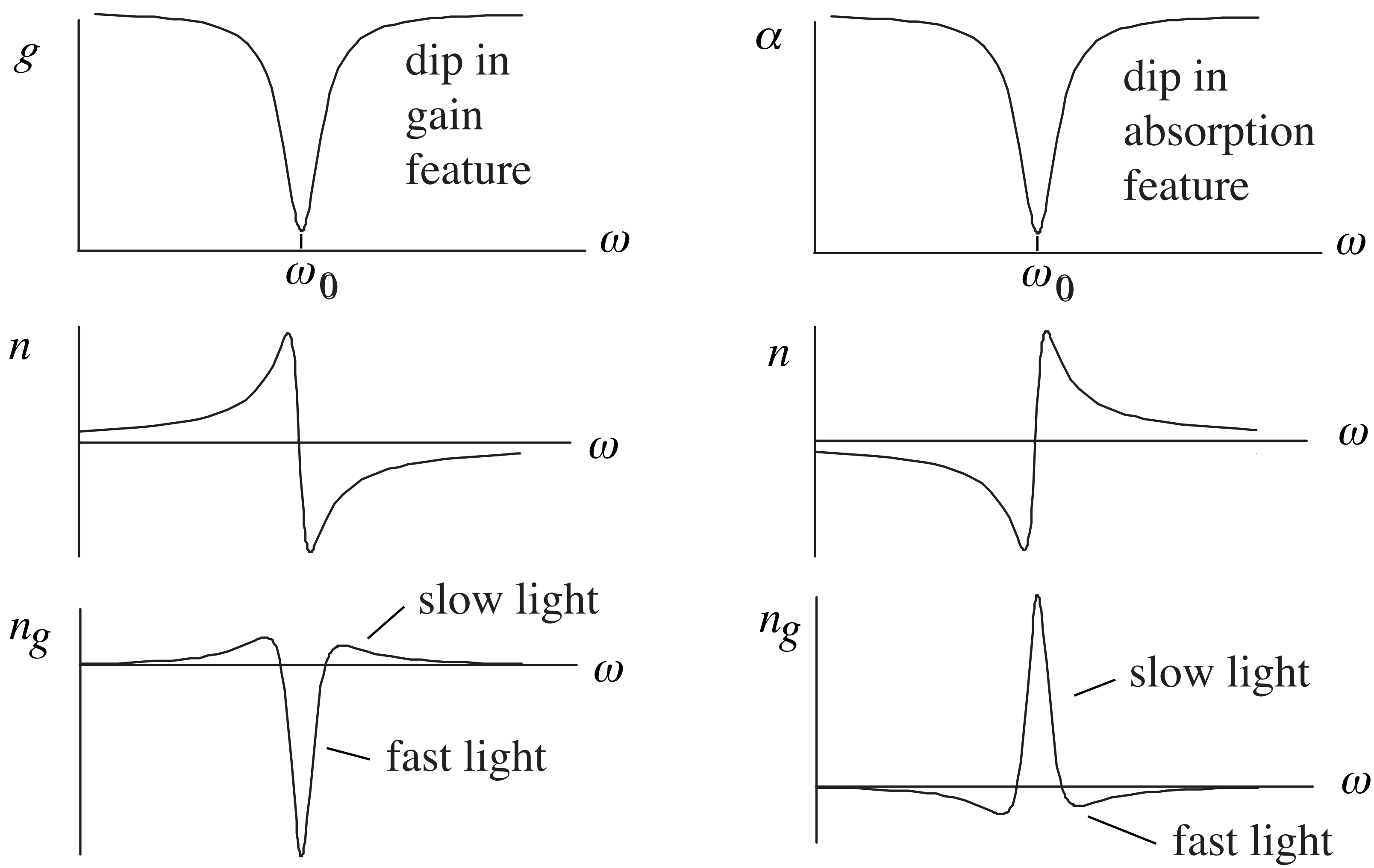
Sharp spectral features produce large dispersion.

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

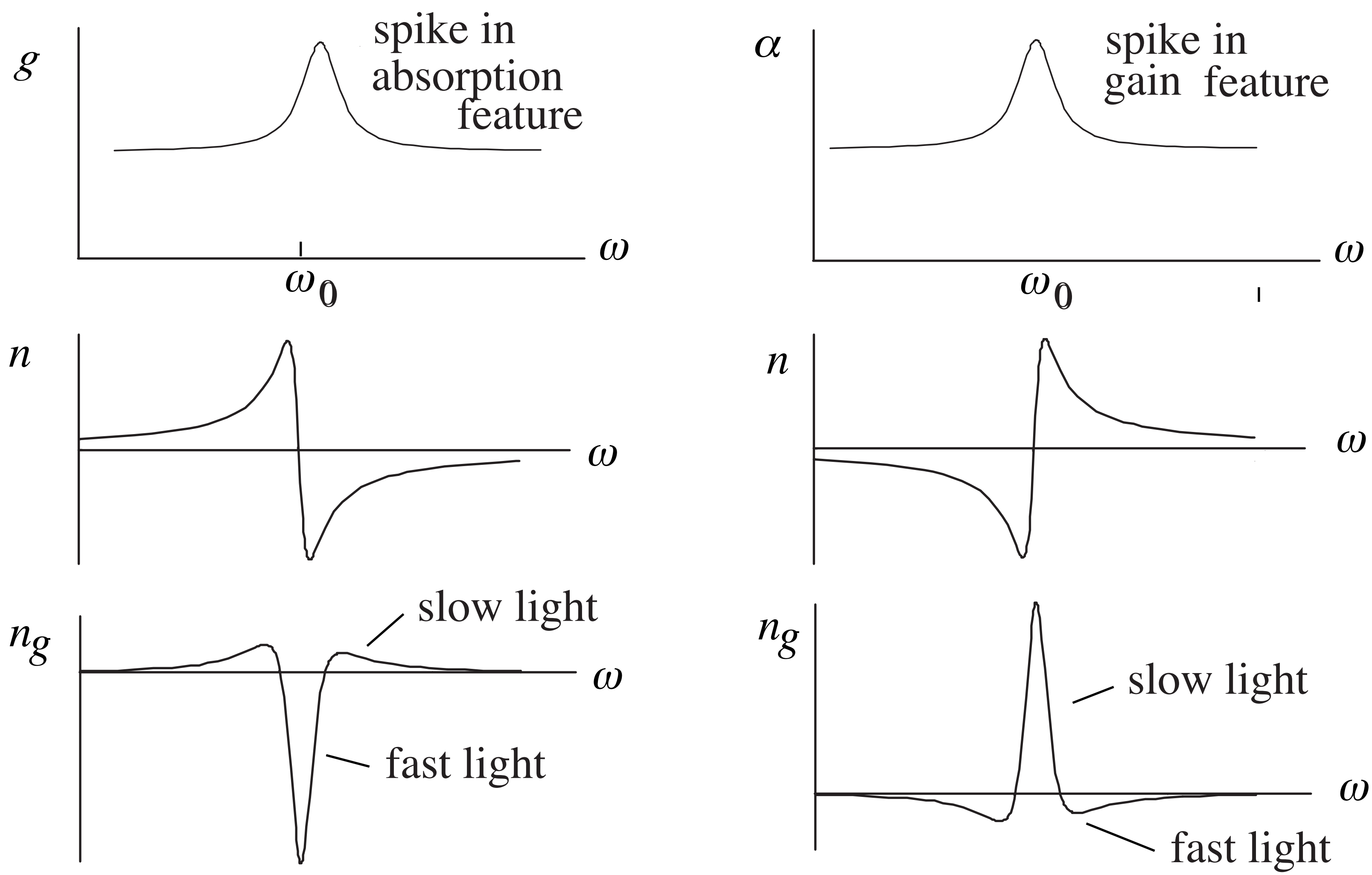


# How to Create Slow and Fast Light II – Use Dip in Gain or Absorption Feature



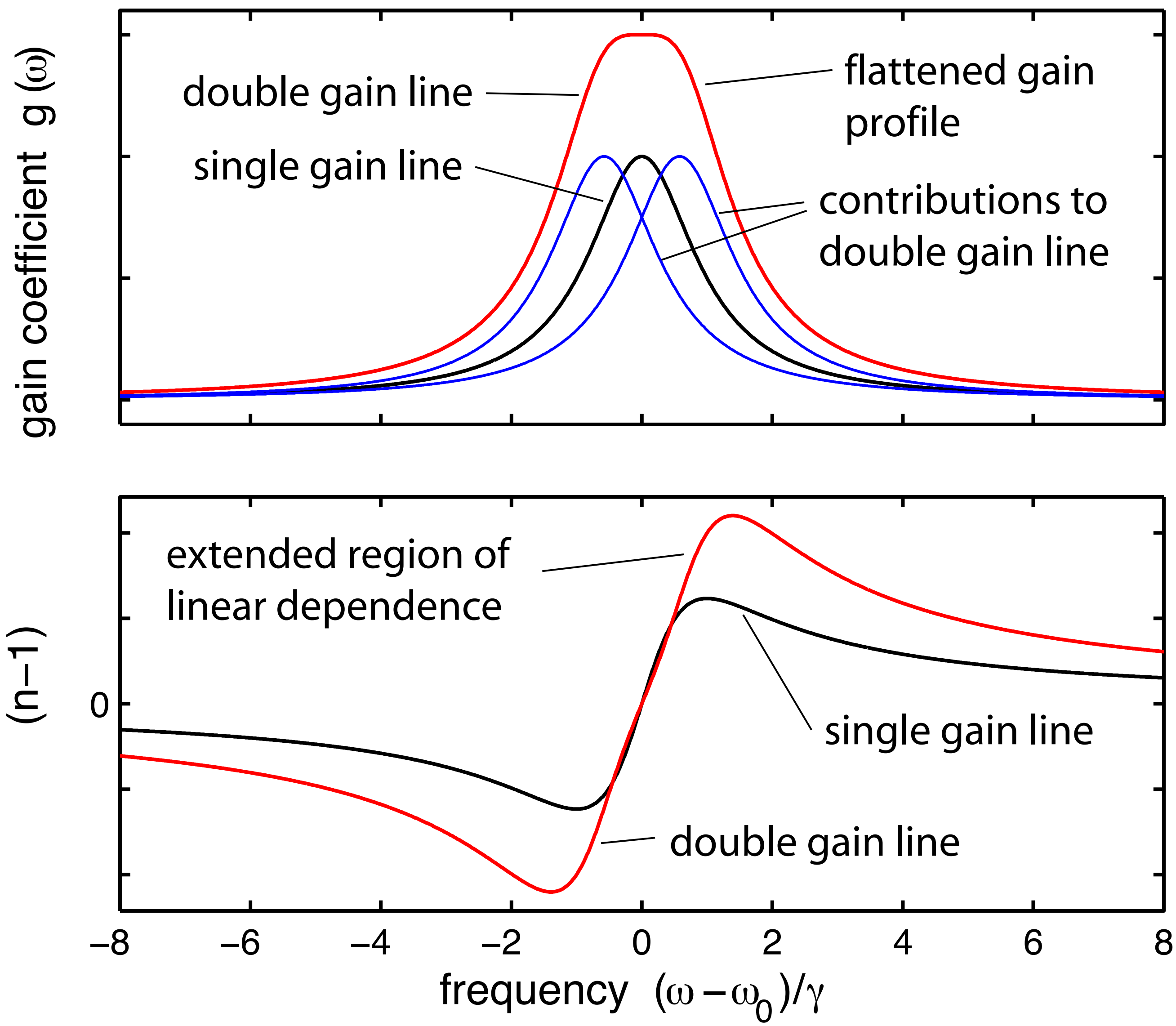

Narrow dips in gain and absorption lines can be created by various nonlinear optical effects, such as electromagnetically induced transparency (EIT), coherent population oscillations (CPO), and conventional saturation.

# How to Create Slow and Fast Light III – Use Spike (Antidip) in Gain or Absorption Feature




Narrow spkies in gain and absorption lines can be created by various nonlinear optical effects, such as electromagnetically induced absorption (EIA), coherent population oscillations (CPO), and reverse saturation.

# How to Create Slow and Fast Light IV – Dispersion Management




M. D. Stenner, M. A. Neifeld, Z. Zhu, A. M. C. Dawes, and D. J. Gauthier, Optics Express 13, 9995 (2005).

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

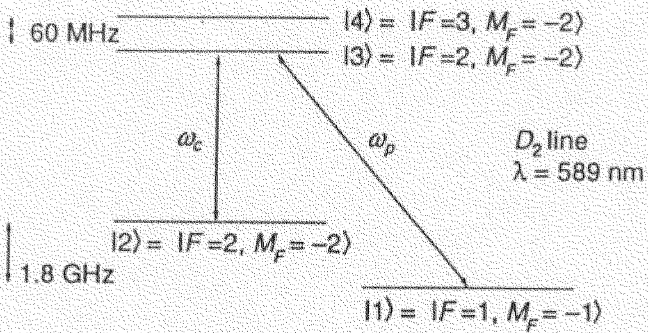
**Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§**

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

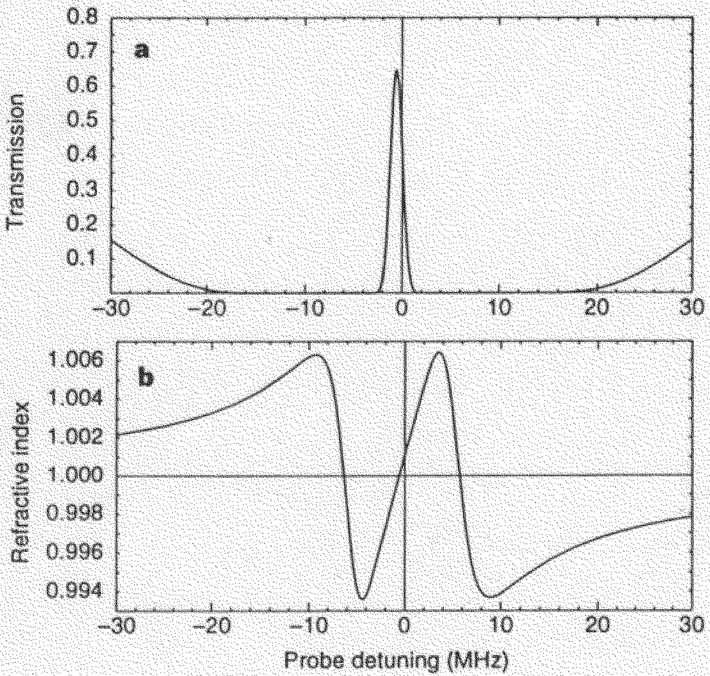
† *Department of Physics,* § *Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*

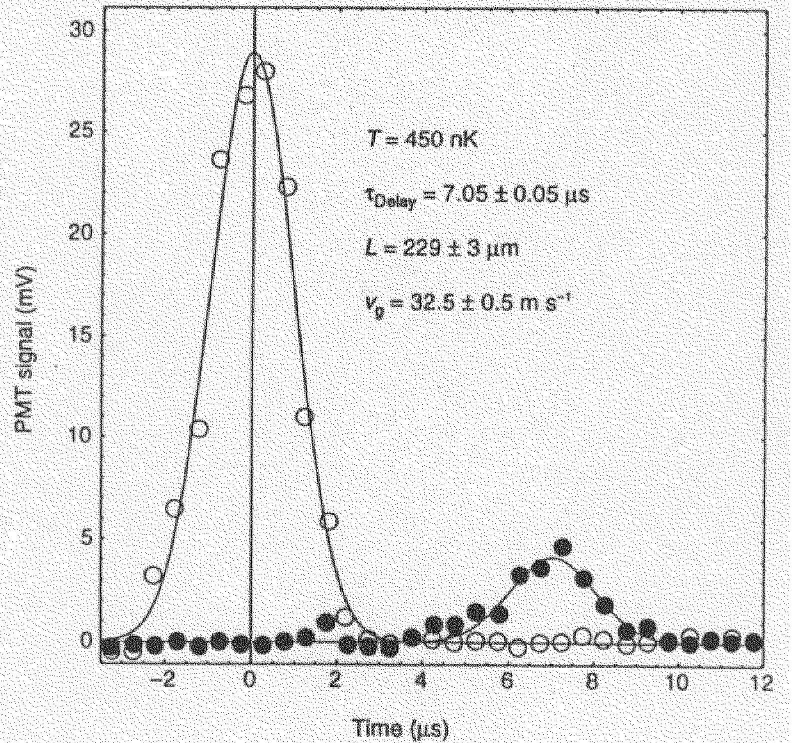
‡ *Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

Nature, 397, 594, (1999).




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



# 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).

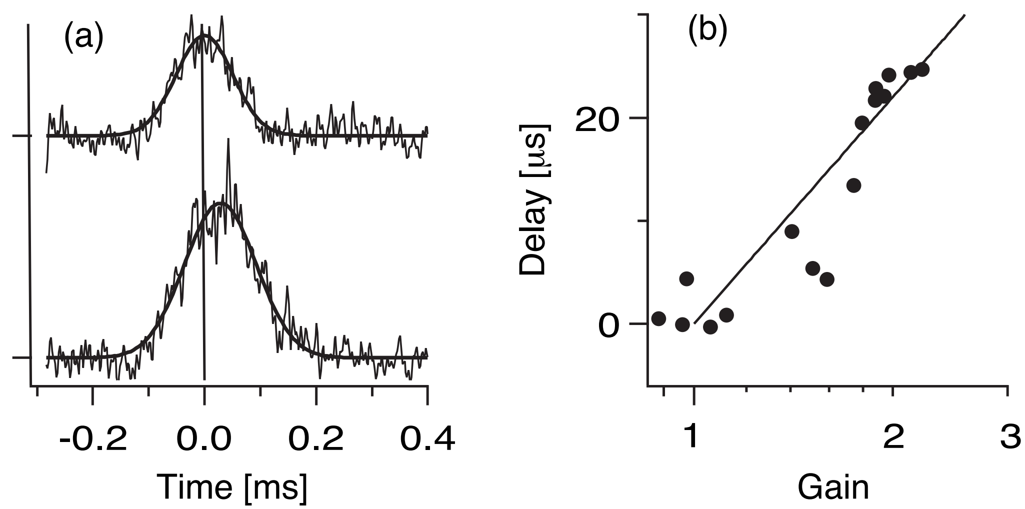



FIG. 3. Pulse delay due to light amplification. (a) About 20 ms delay was observed when a Gaussian pulse of about 140 ms width and 0.11 mW/cm$^2$ peak intensity was sent through the dressed condensate (bottom trace). The top trace is a reference taken without the dressed condensate. Solid curves are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

# Challenge / Goal (2003)

Slow light is 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

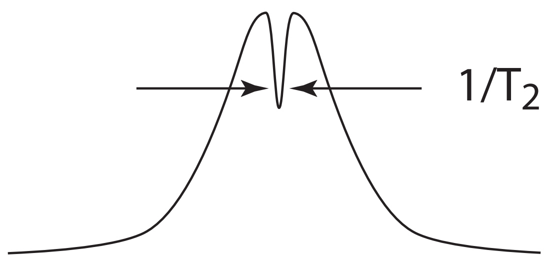
Recall that $n_g = n + \omega(dn/d\omega)$. Need a large $dn/d\omega$. (How?)

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

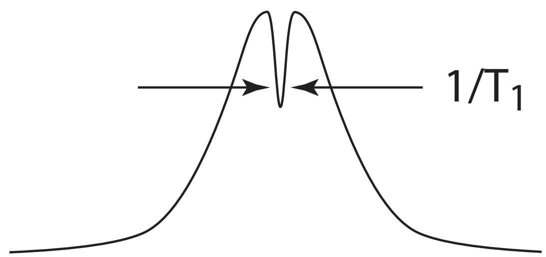
Well-known "trick" for doing so:

Make use of spectral holes due to population oscillations.

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



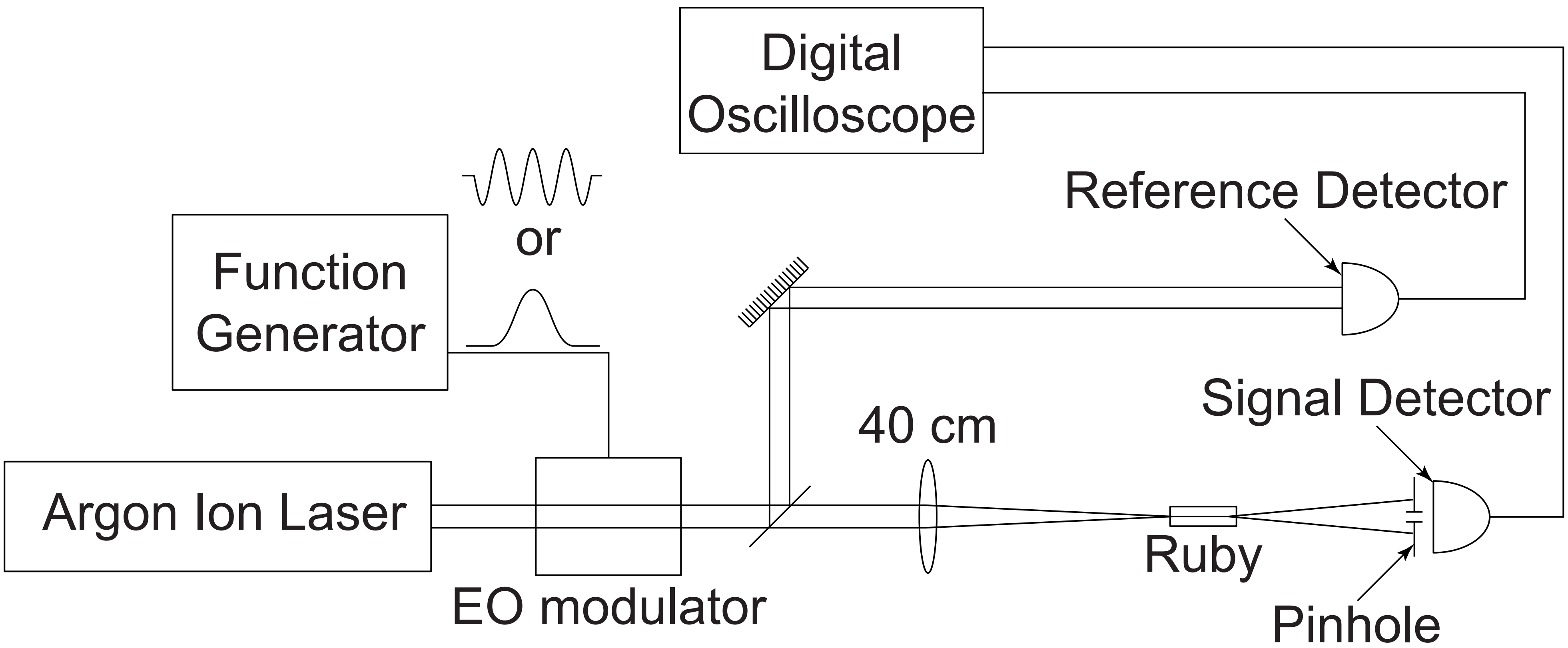

inhomogeneously broadened medium




homogeneously broadened medium (or inhomogeneously broadened)

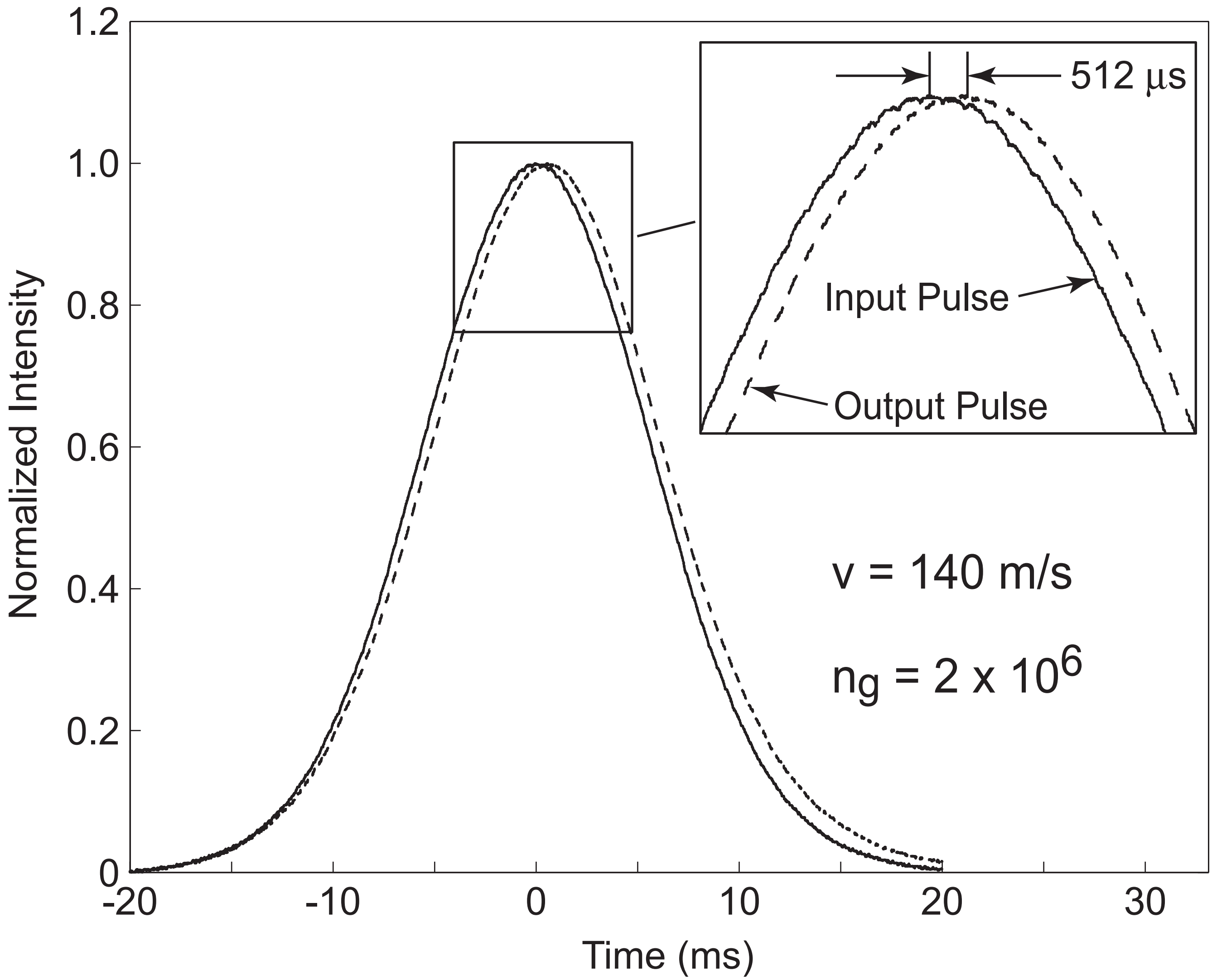
PRL 90,113903(2003).

# Slow Light Experimental Setup



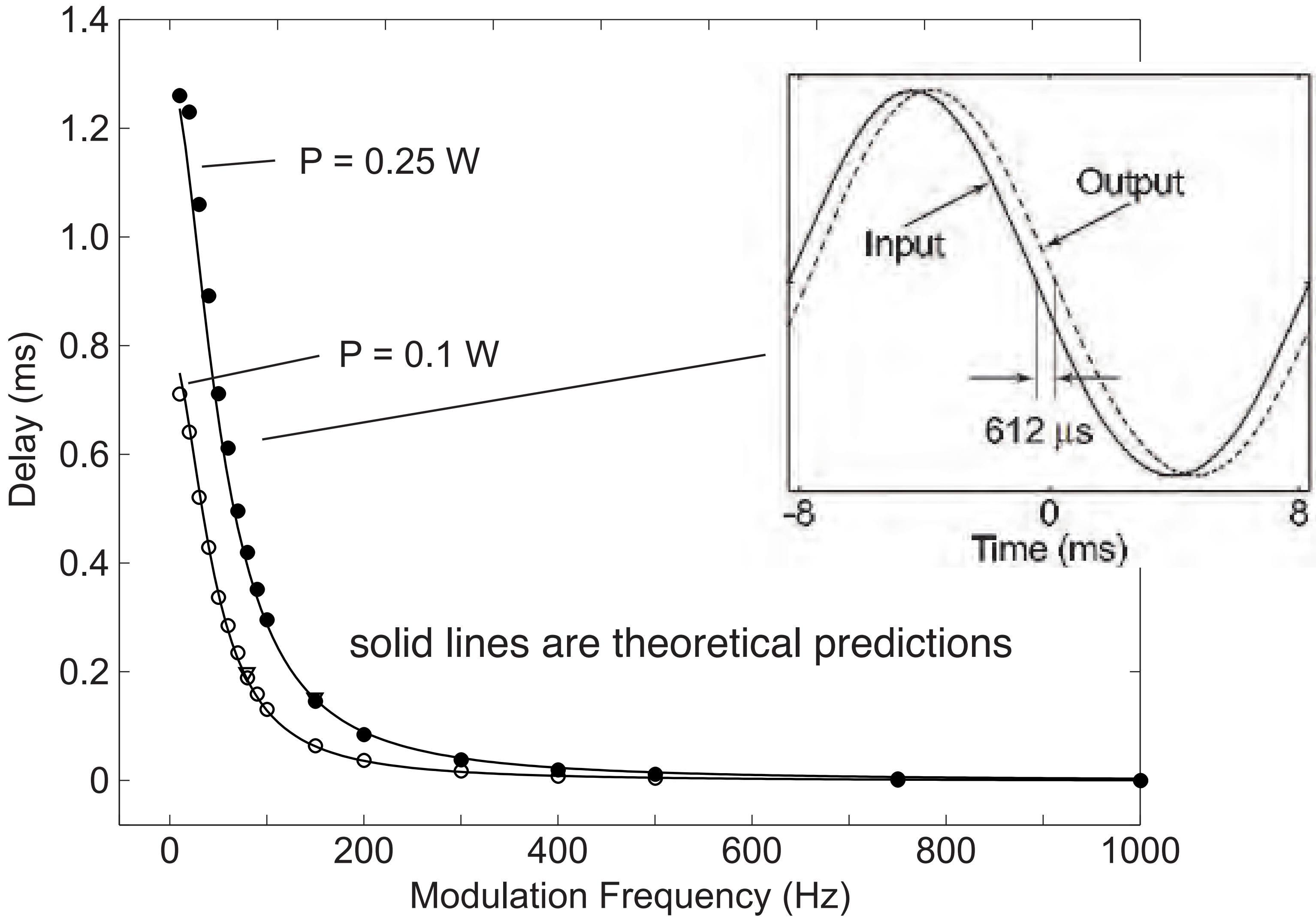

7.25-cm-long ruby laser rod (pink ruby)

# Gaussian Pulse Propagation Through Ruby



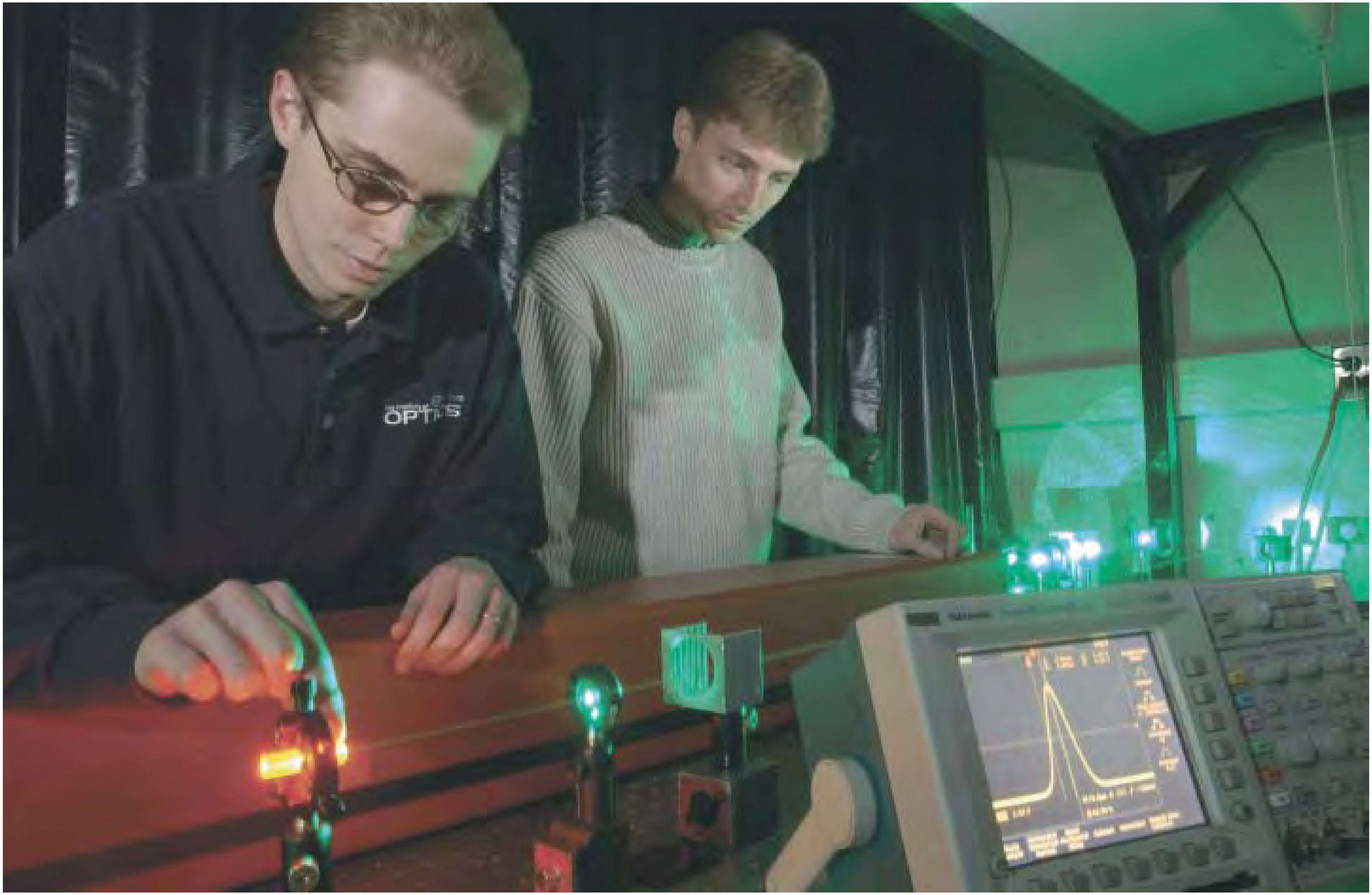

No pulse distortion!

# Measurement of Delay Time for Harmonic Modulation



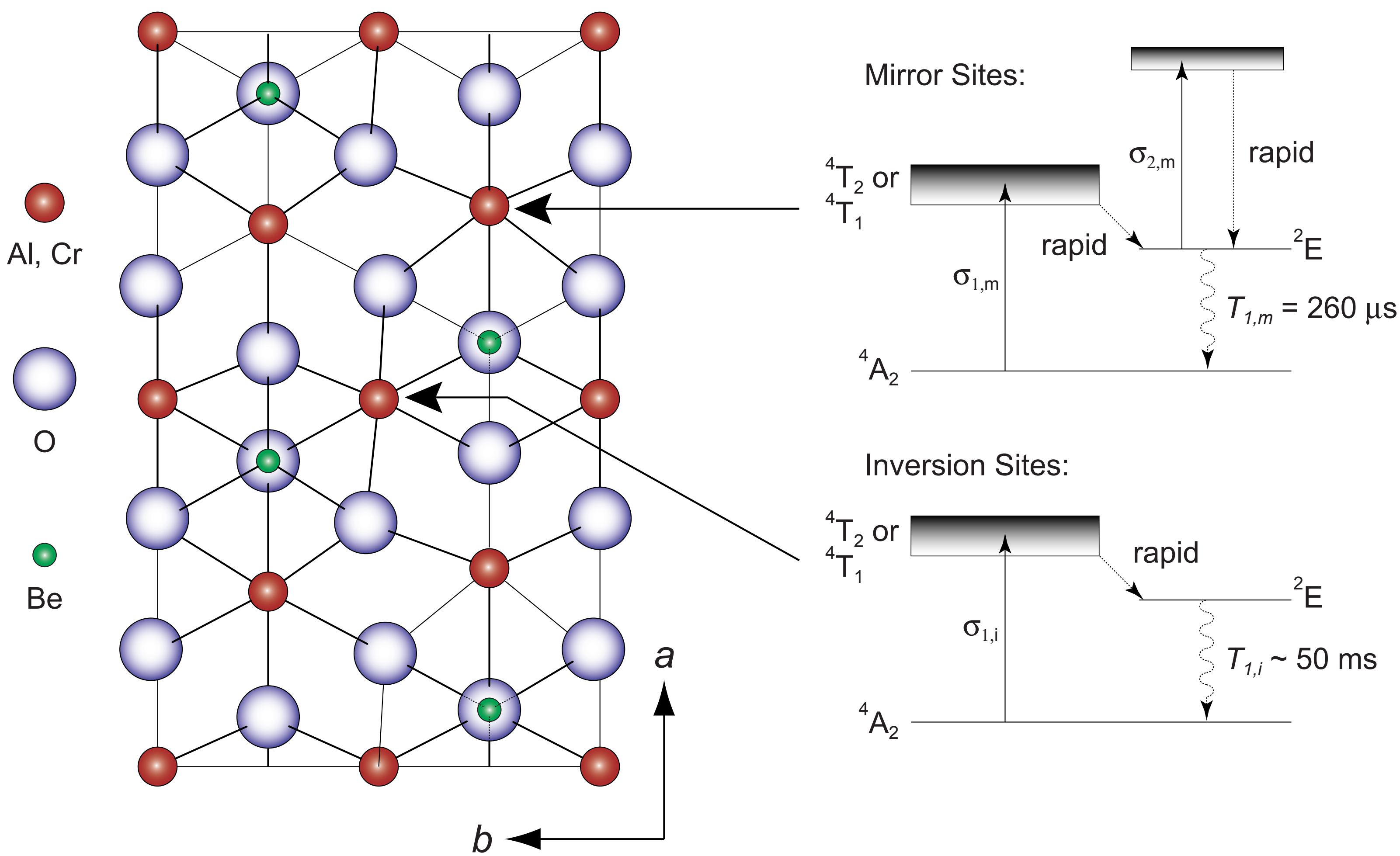

For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

# Matt Bigelow and Nick Lepeshkin in the Lab



# Alexandrite Displays both Saturable and Reverse-Saturable Absorption

- Both slow and fast propagation observed in alexandrite

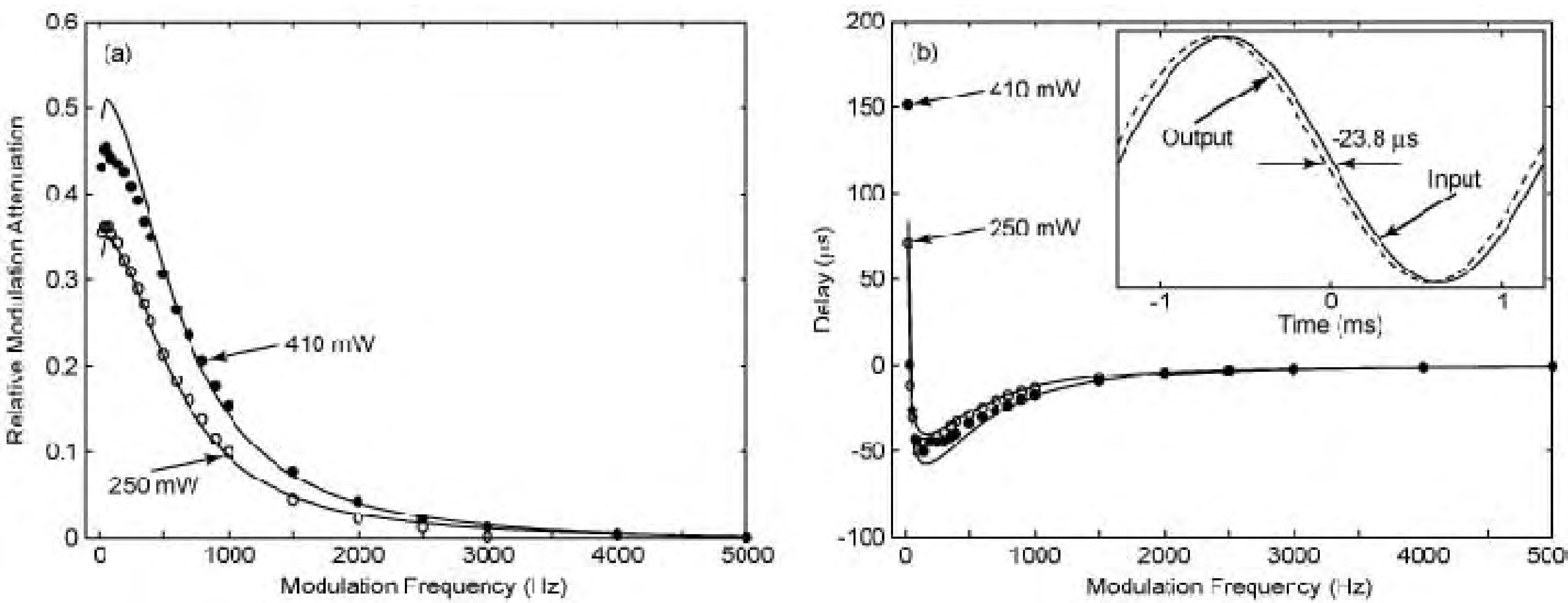



Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

# 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 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:

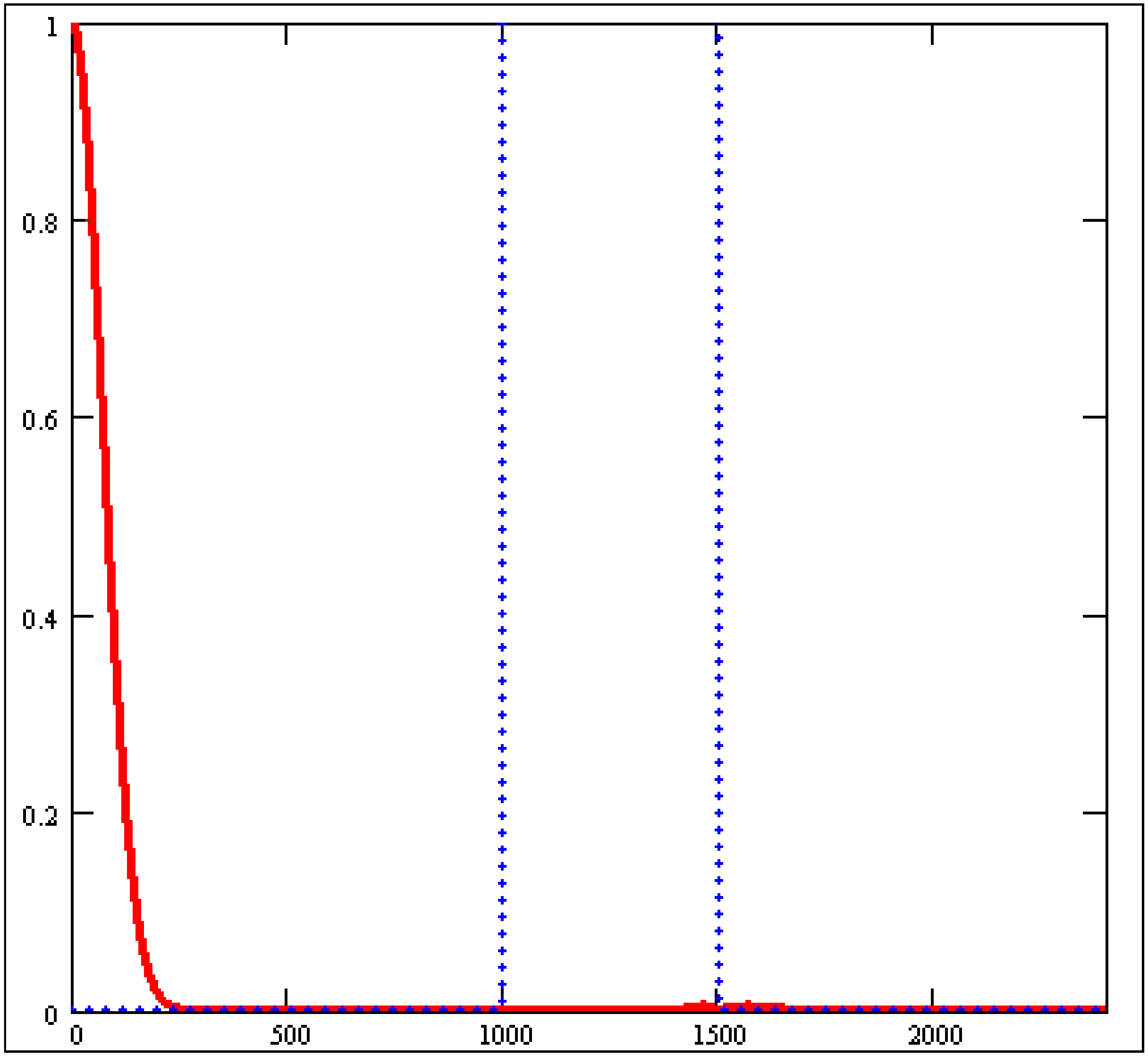
Slow light $v_g = 0.5\ c$

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

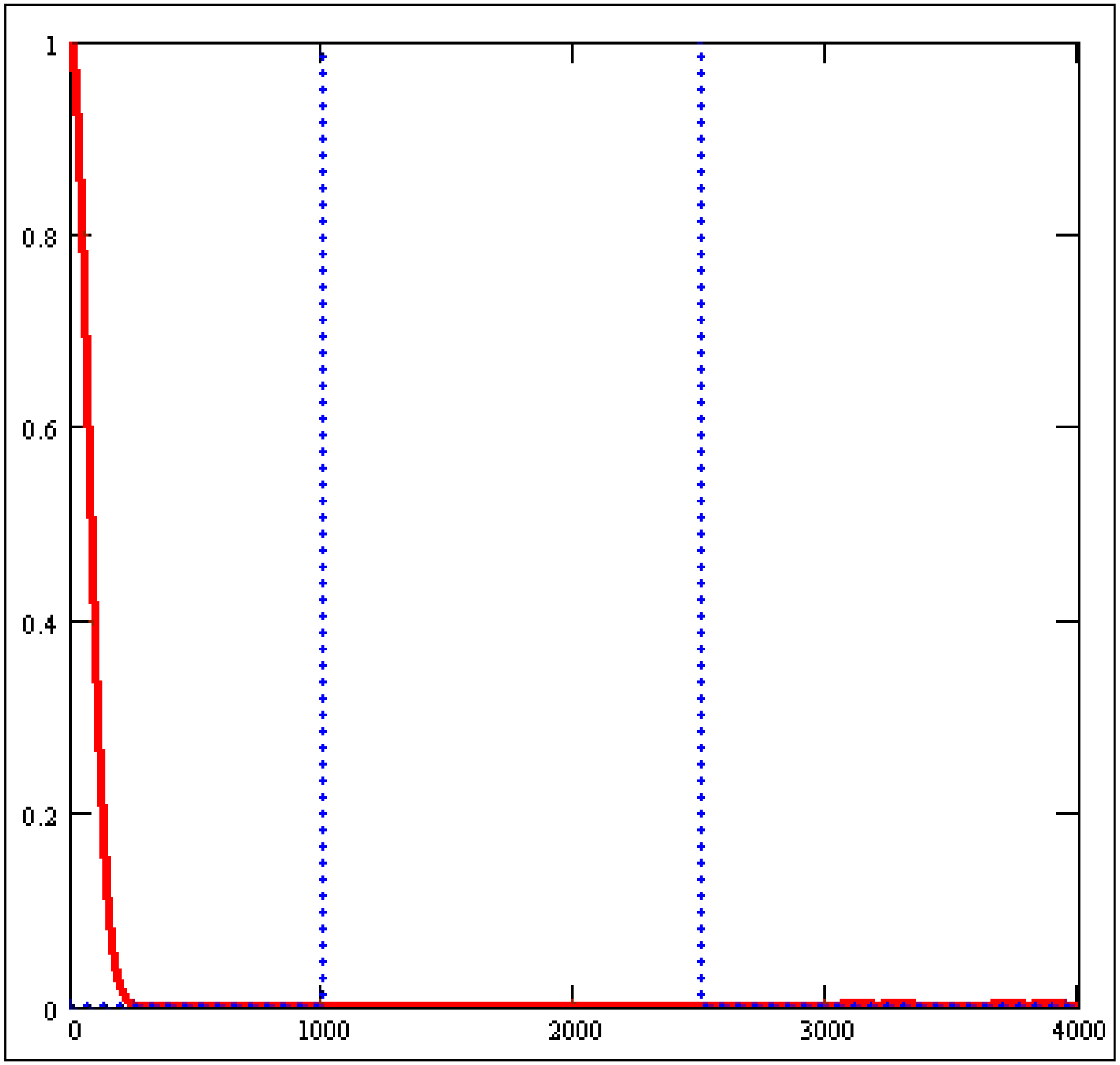
CAUTION: This is a very simplistic model. It ignores GVD and spectral reshaping.

See also Dogariu et al. Opt. Express 8, 344 (2001) and Milonni (2005).

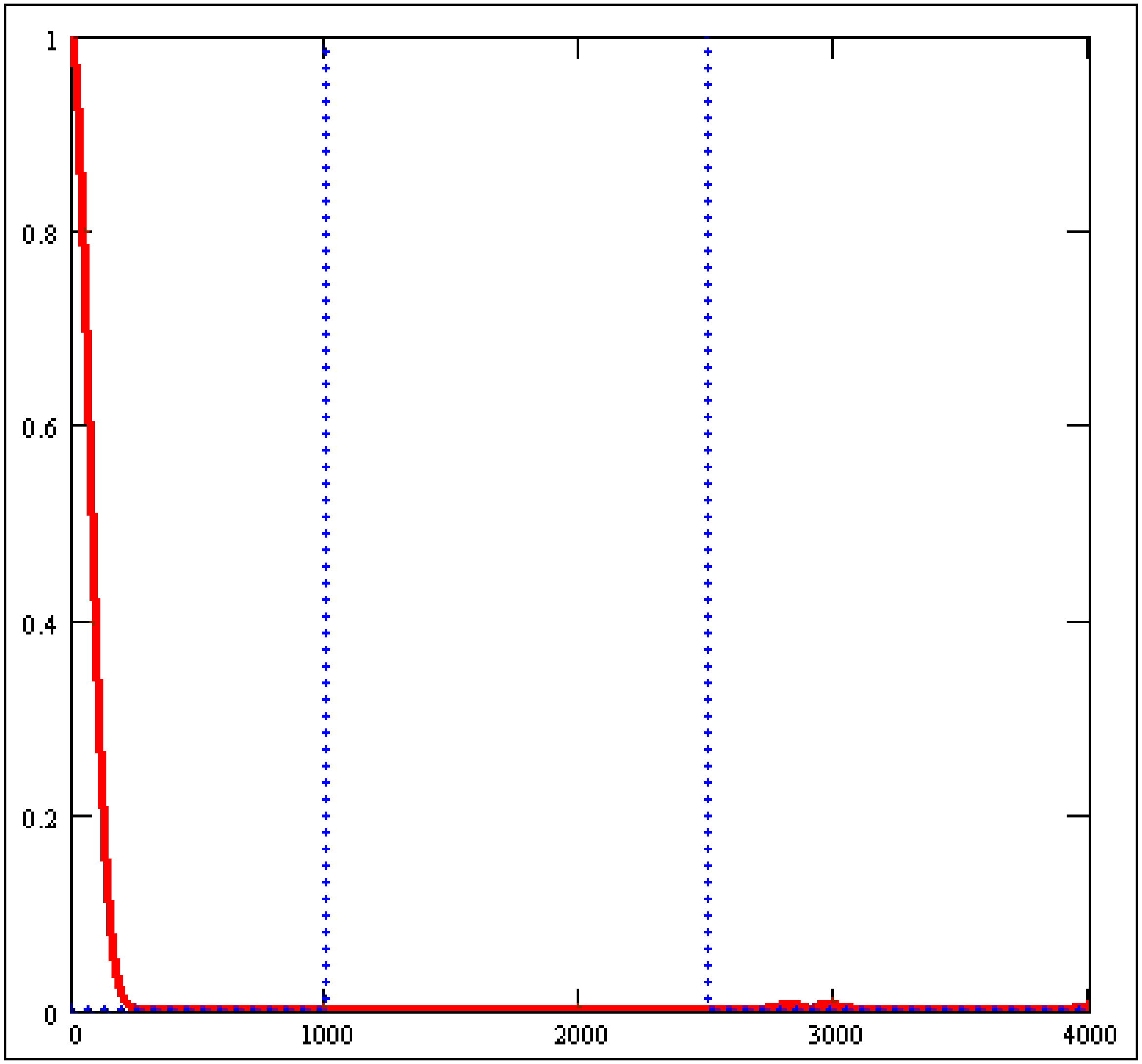
# Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5\ c$)



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

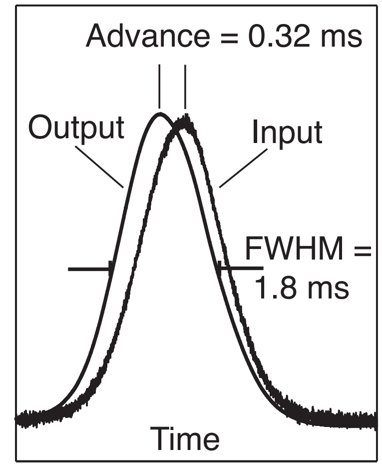


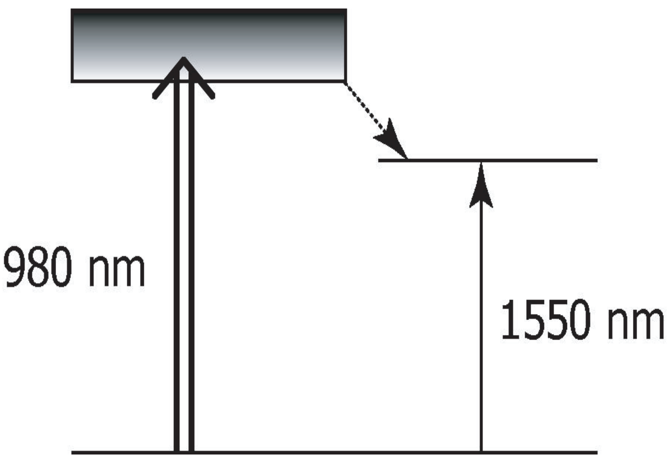
# Pulse Propagation through a Fast-Light Medium ($n_g$ = -.5, $v_g$ = -2 c)

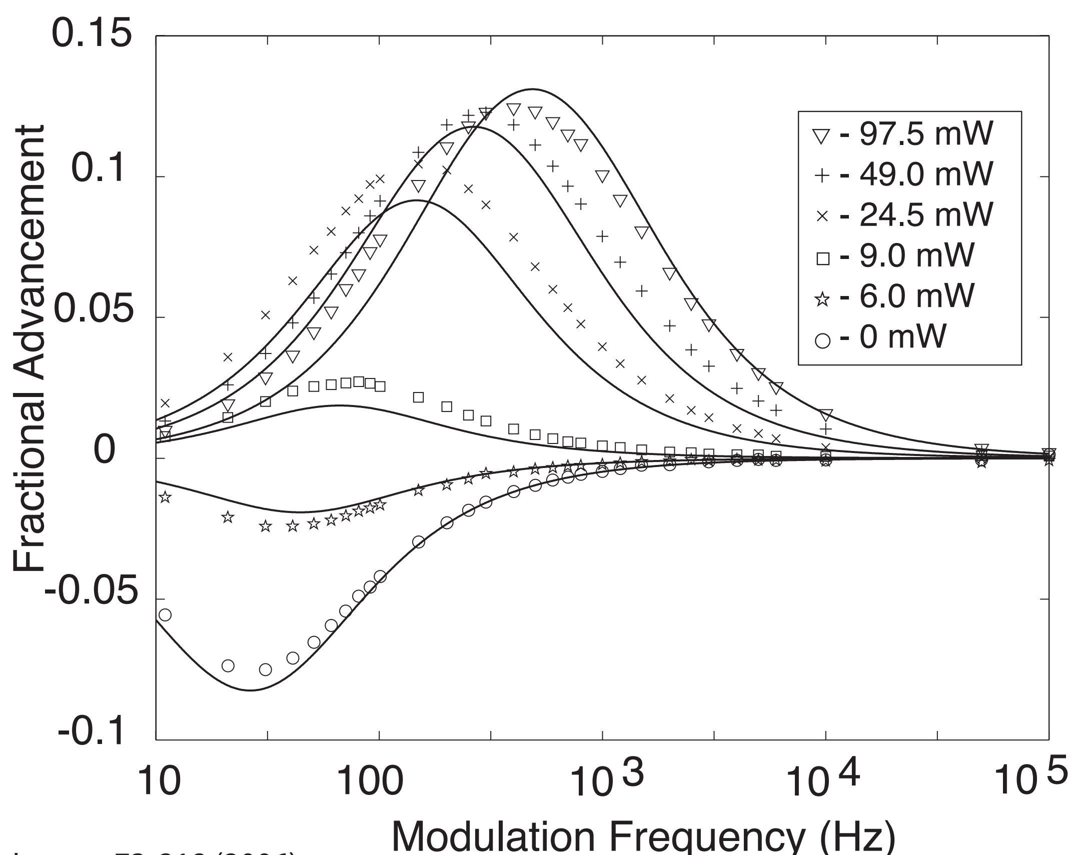


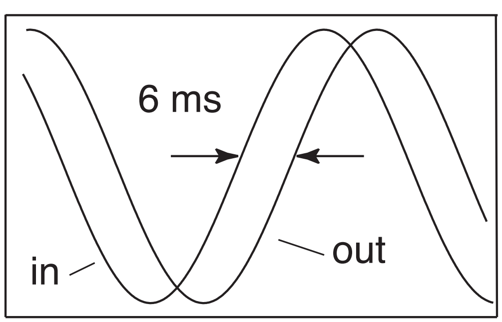
# Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



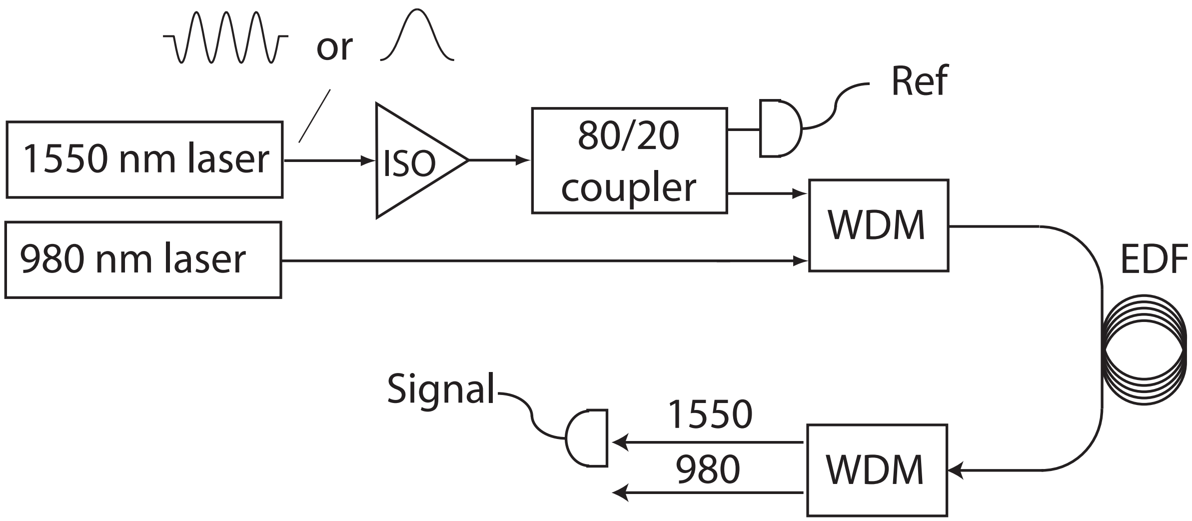




Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

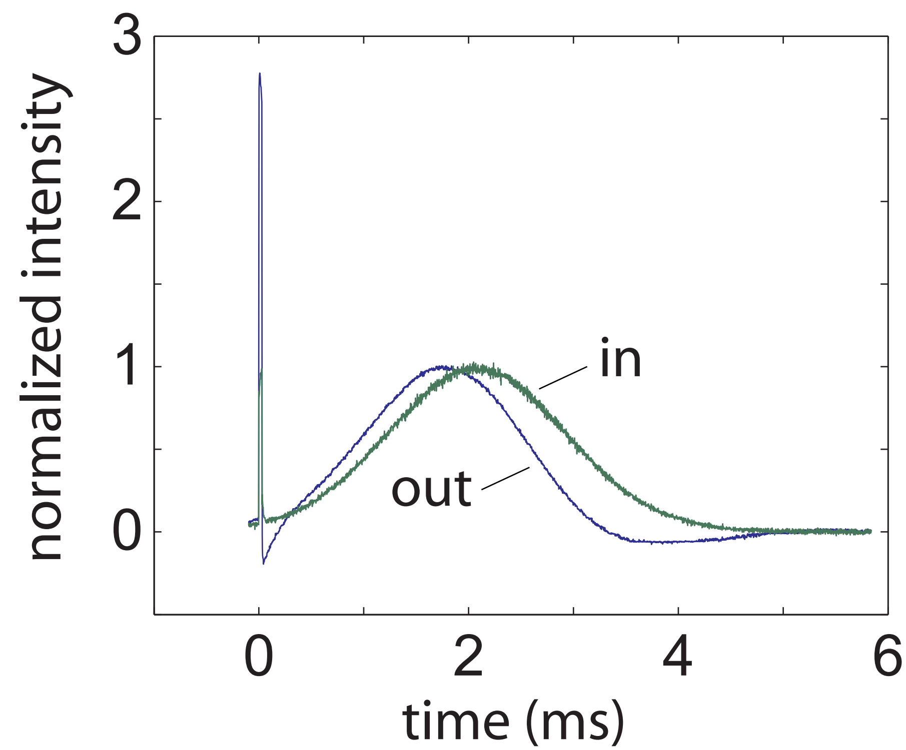
# Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier




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

Procedure

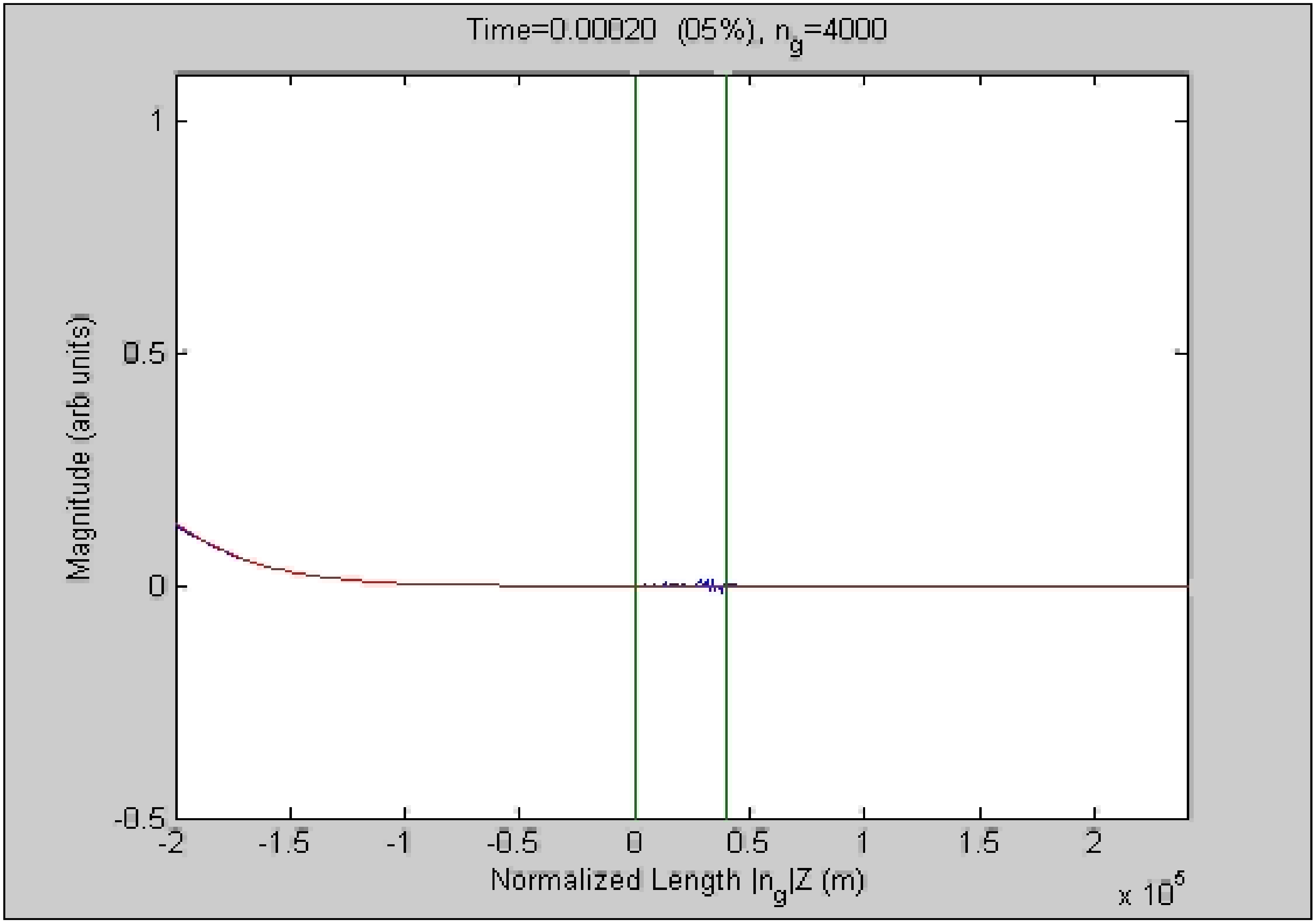
- cutback method
- couplers embedded in fiber




G. M. Gehring, A. Schweinsberg, C. Barsi, N. Kostinski, R. W. Boyd, Science 312, 985 2006.

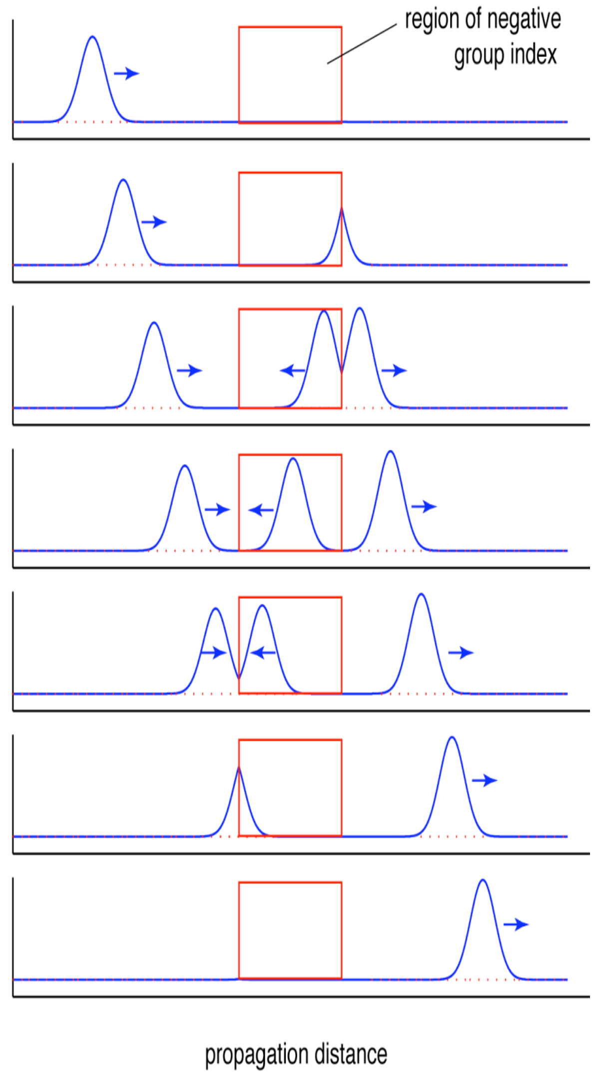
# Experimental Results:  Backward Propagation in Erbium-Doped Fiber

## Normalized:  (Amplification removed numerically)

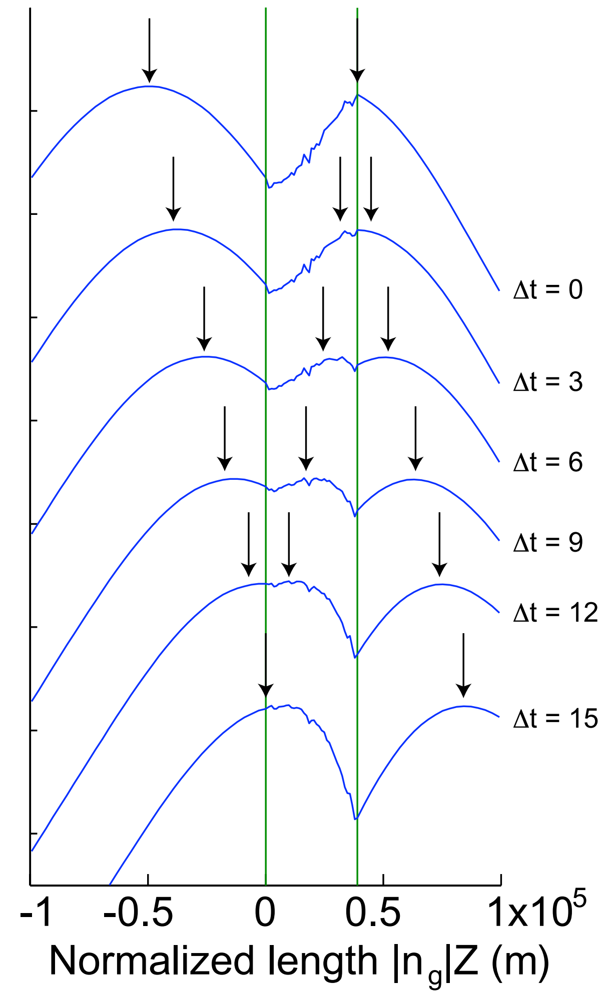


# Observation of "Backwards" Pulse Propagation

- conceptual prediction




- laboratory results




- 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.

# 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



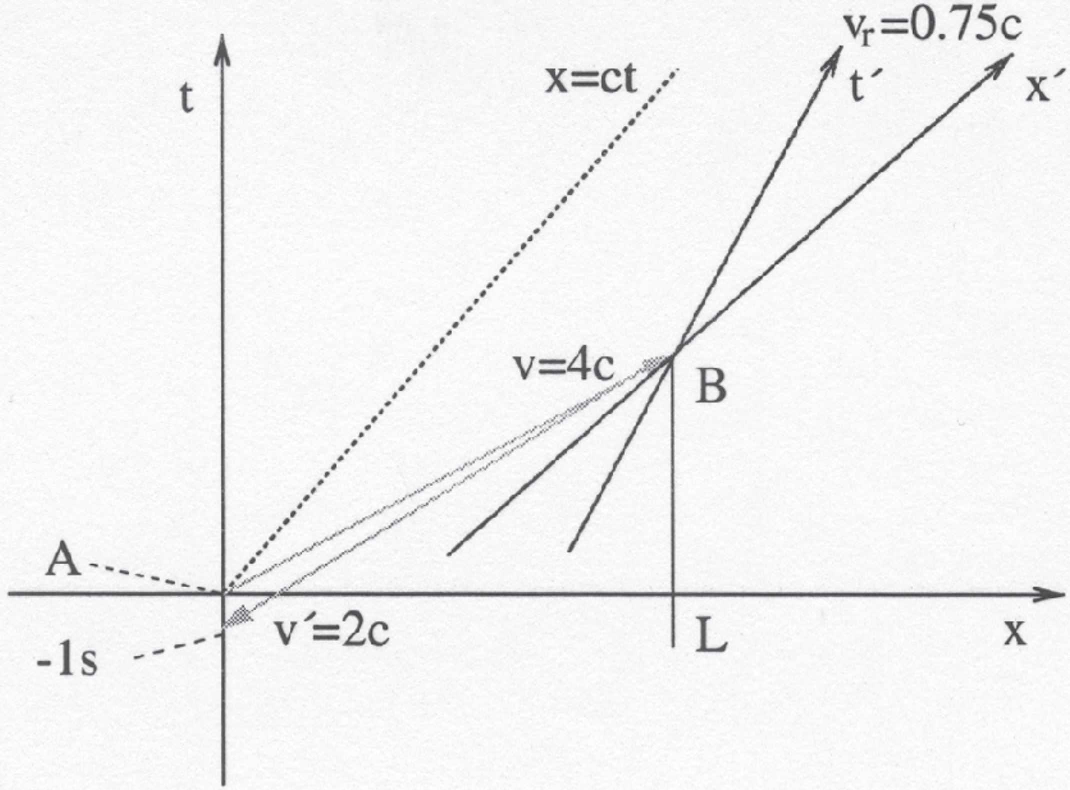
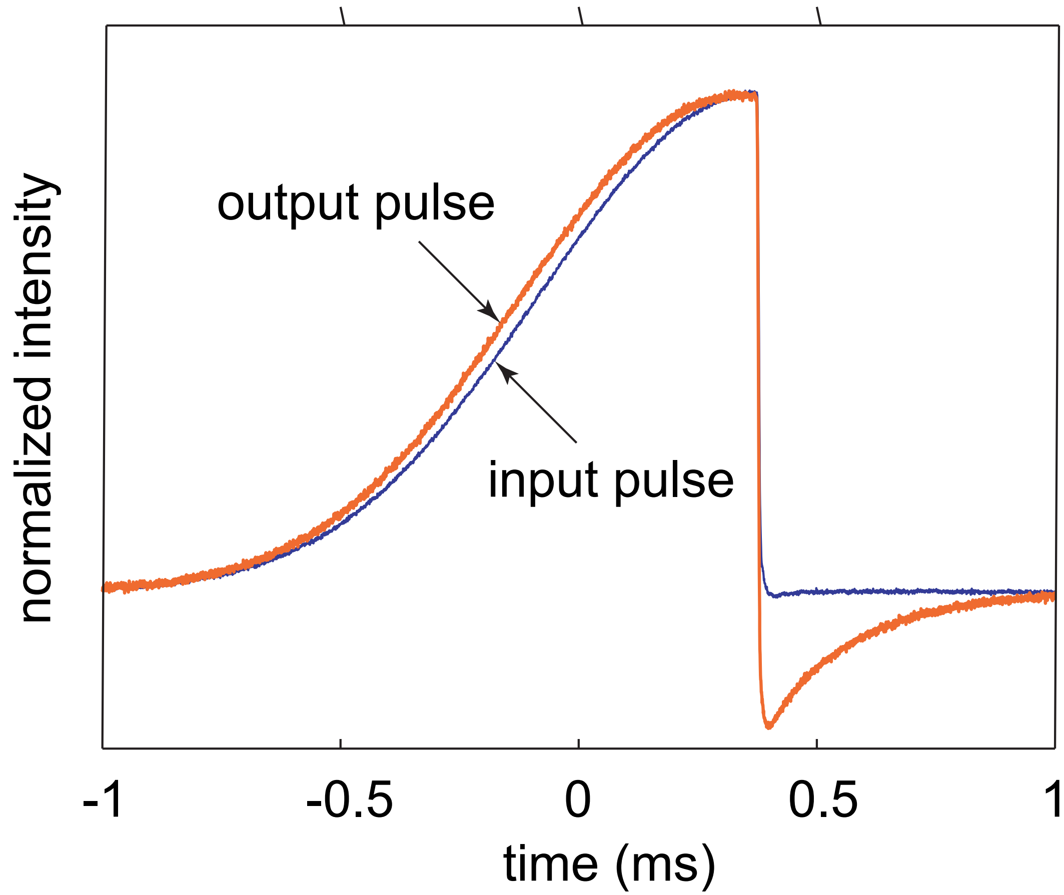



**Fig. 6** Coordinates of two inertial observers **A** (0,0) and **B** with $O(x,t)$ and $O'(x',t')$ moving with a relative velocity of 0.75*c*. The distance *L* between **A** and **B** is 2000000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v_s' = 2c$. The numbers in the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

Ann. Phys. (Leipzig) 11, 2002.

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




Smooth part of pulse propagates at group velocity

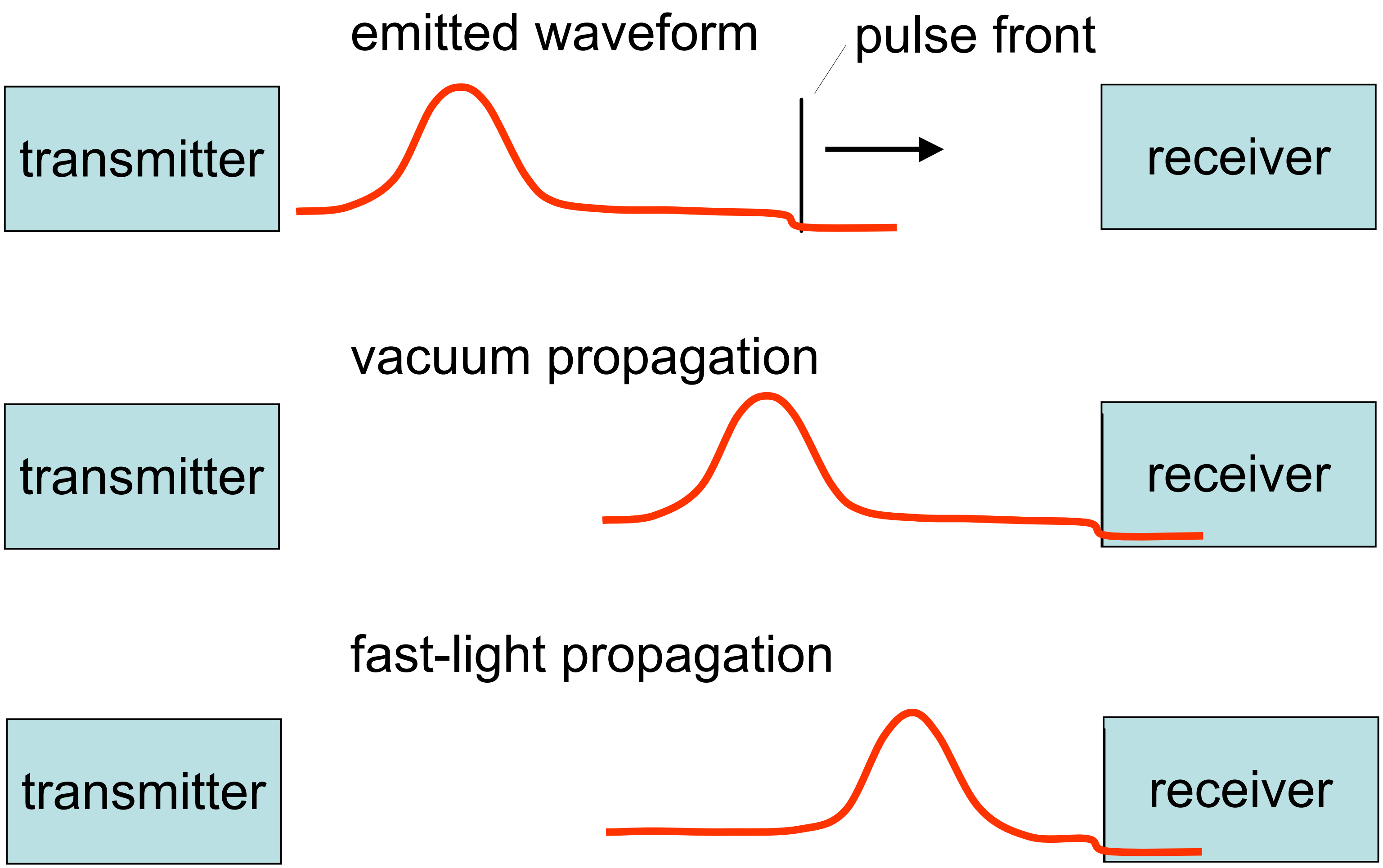
Discontinuity propagates at phase velocity

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




Gauthier and Boyd, Photonics Spectra, p. 82 January 2007.

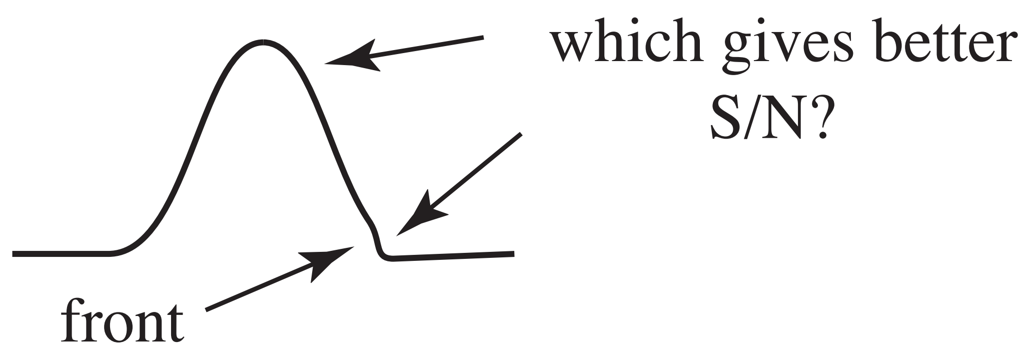
# Information Velocity – Tentative Conclusions

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

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

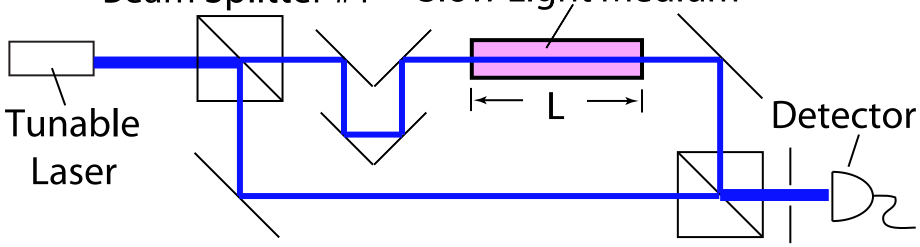
In a real communication system it would be really stupid to transmit pulses containing so much energy that one can reliably detect the very early leading edge of the pulse.



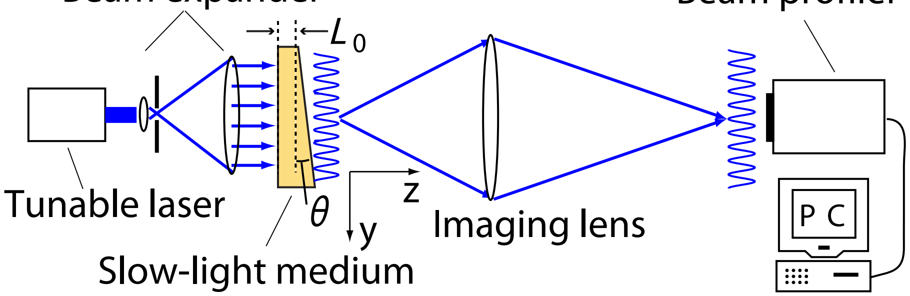
# Interferometry and Slow Light

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

Typical interferometer:




We use $CdS_xSe_{1-x}$ as our slow-light medium

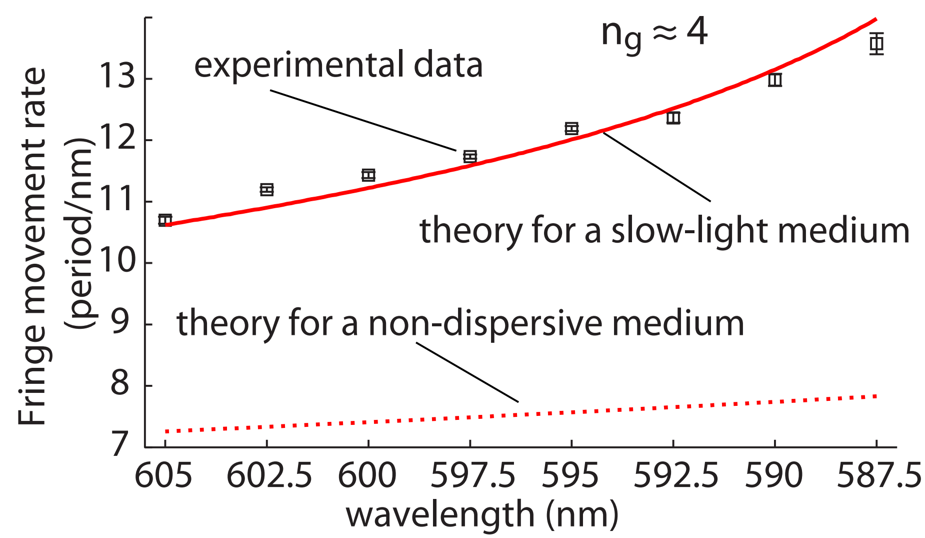



Here is why it works:

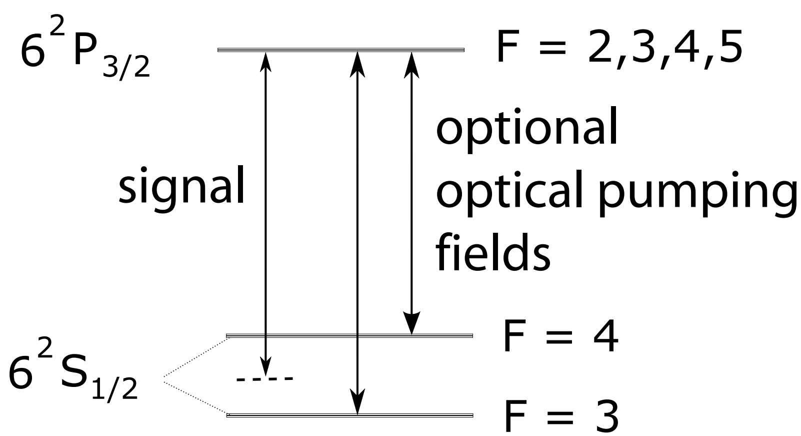
$$\frac{d\Delta\phi}{d\omega} = \frac{d}{d\omega}\left(\frac{\omega n L}{c}\right) = \frac{L}{c}\left(n + \omega\frac{dn}{d\omega}\right) = \frac{L n_g}{c}$$

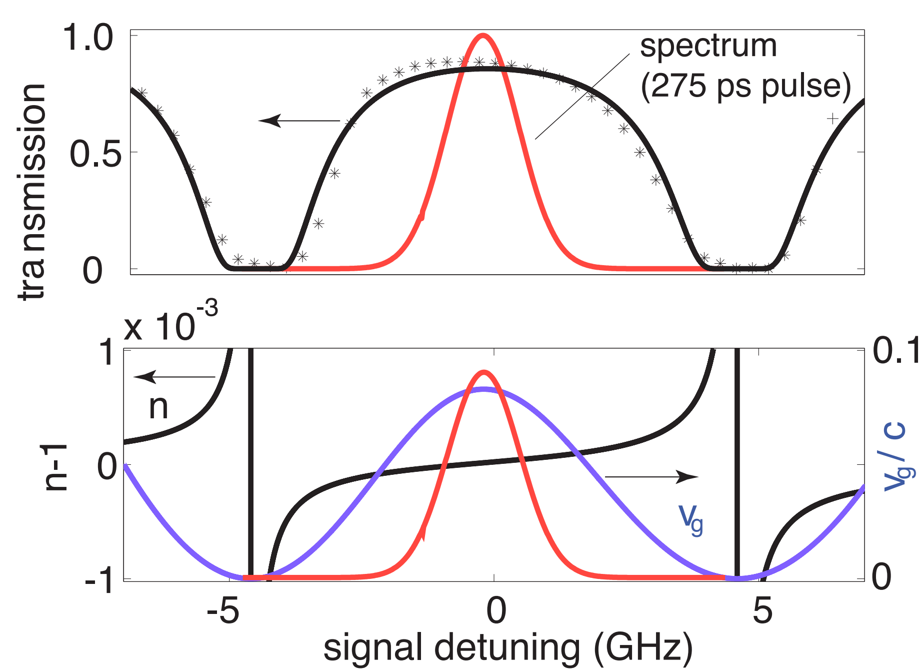
Shi, Boyd, Gauthier, Dudley, Opt. Lett., 32, 915, 2007.

Our experimental results

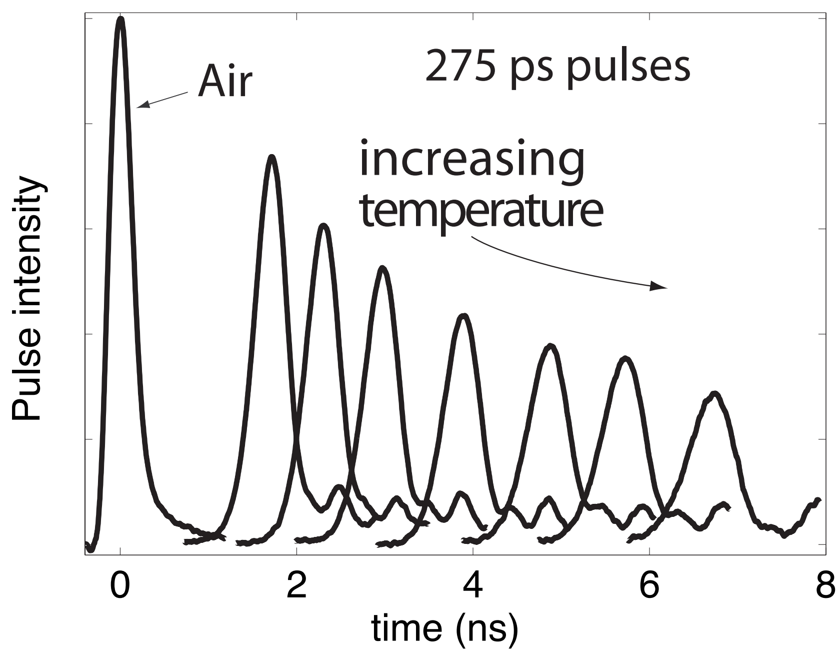


# Tunable Delays of up to 80 Pulse Widths in Atomic Cesium Vapor

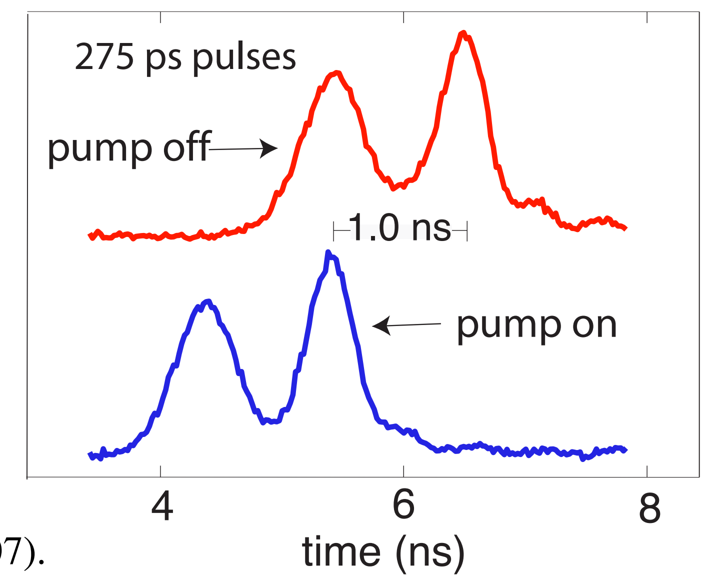



• coarse tuning: temperature




• fine tuning: optical pumping




Camacho, Peck, Howell, Schweinsberg, Boyd, PRL 98, 153601 (2007).

# Fundamental Limits on Slow and Fast Light

Slow Light: There appear to be no fundamental limits on how much one can delay a pulse of light (although there are very serious practical problems).*

Fast Light: But there do seem to be essentially fundamental limits to how much one can advance a pulse of light.

**Why are the two cases so different?****

We have identified two mechanisms that distinguish these two cases!

* Boyd, Gauthier, Gaeta, and Willner, PRA 2005

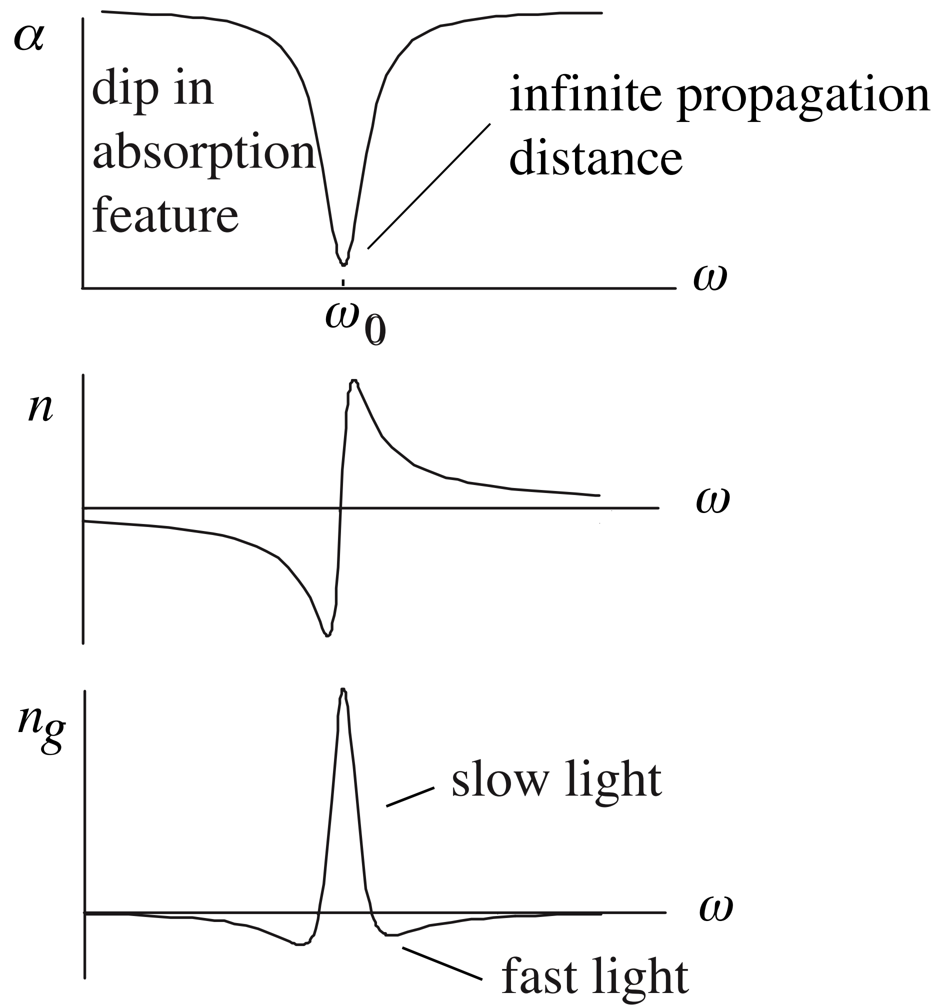
** We cannot get around this problem simply by invoking causality, first because we are dealing with group velocity (not information velocity), and second because the relevant equations superficially appear to be symmetric between the slow- and fast-light cases.

# Why is there no limit to the amount of pulse delay?

At the bottom of the dip in the absorpton, the absorption can in principle be made to vanish.  There is then no limit on how long a propagation distance can be used.

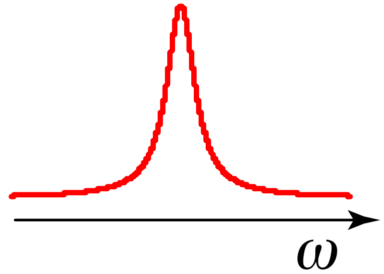
But this “trick”works only for slow light.

Why?  Because for a system based on gain, the gain cannot become too large at any frequcncy, or else ASE will occur.

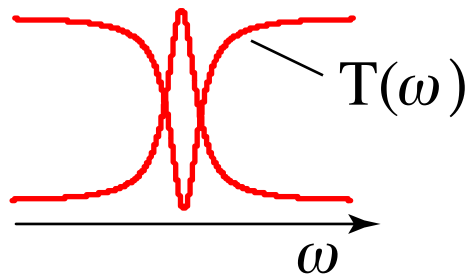


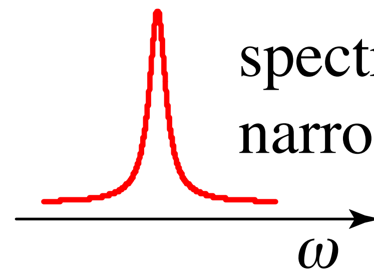
# Influence of Spectral Reshaping
## (Line-Center Operation, Dip in Gain or Absorption Feature)

input pulse



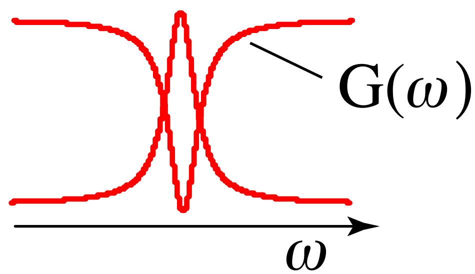

output pulse
slow-light

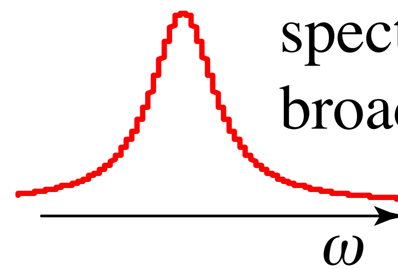



spectrally
narrowed pulse

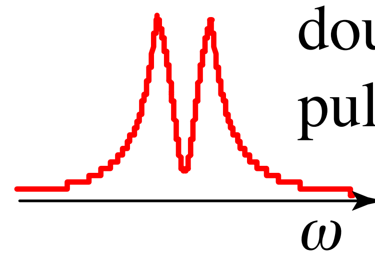
output pulse
fast-light




spectrally
broadened pulse

for still longer propagation distances, the pulse breaks up spectrally and temporally




double-humped
pulse

# Why can one delay (but not advance) a pulse by an arbitrarily large amount?

Two crucial differences between slow and fast light

(1) First, note that we cannot use gains greater than approximately exp(32) at any frequency to avoid ASE. And we cannot have absorption larger than T = exp(-32) at the signal frequency, so signal can be measured. (Of course, the argument does not hinge on the value 32.) When examined quantitatively, these constraints impose a limit of at most several pulse-widths of delay or advancement.

$$\frac{\Delta T}{T} = \frac{1}{2}\sqrt{\alpha L}$$

One can overcome these constraints by using a deep hole in an absorption feature, but this trick works only for slow light, as we have just seen.

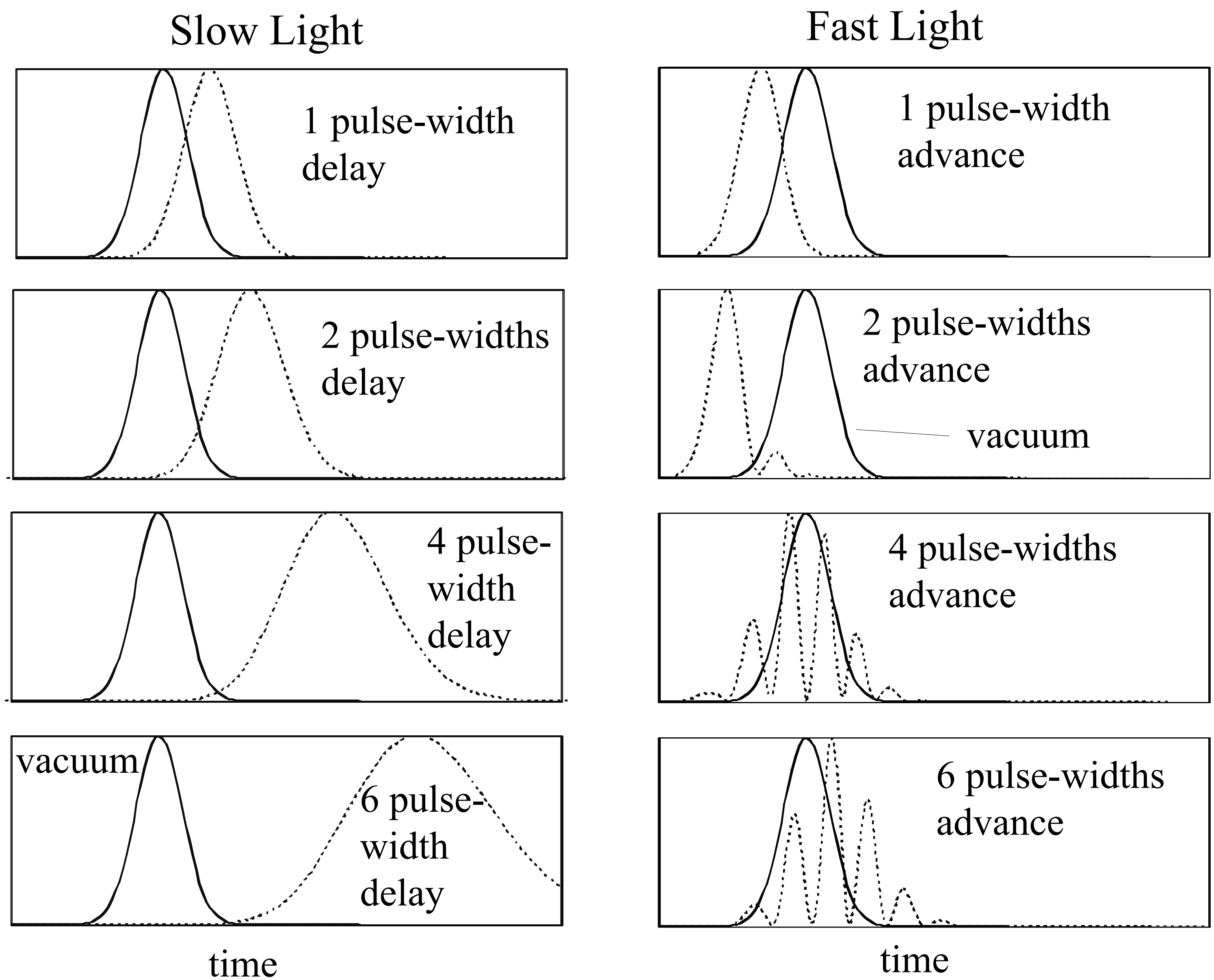
(2) Spectral reshaping of the pulse is the dominant competing effect in most slow/fast light systems. This also behaves differently for slow and fast-light systems, as we shall now see.

# Numerical Results: Propagation through a Linear Dispersive Medium

Fast light:
Lorentzian absorption line
T = exp(-32)
vary line width to control advance

Slow light:
Lorentzian gain line
T = exp(+32)
vary line width to control delay

Same Gaussian input pulse in all cases



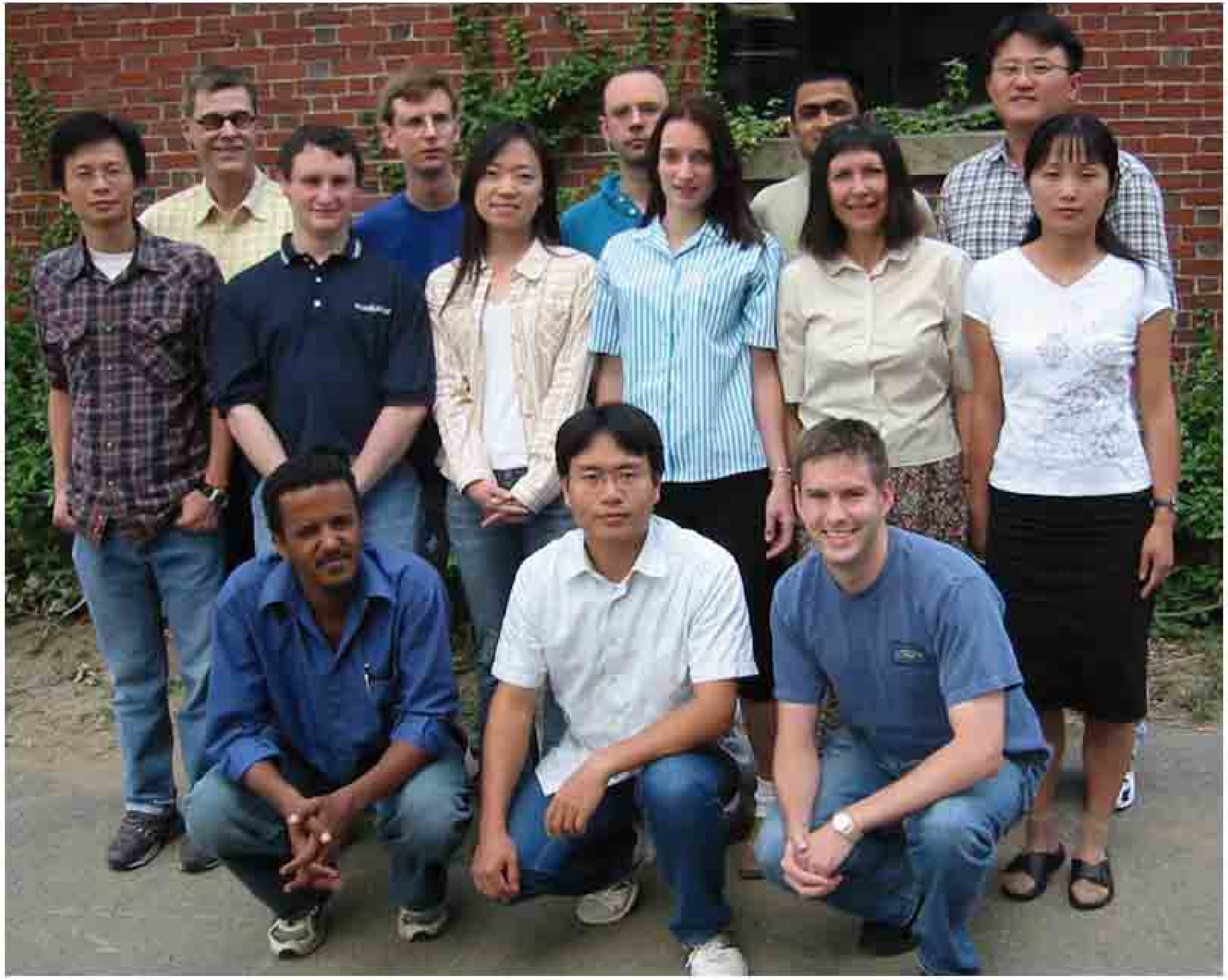
# Summary

Slow-light techniques hold great promise for applications in telecommunications

Good progress being made in devloping new slow-light techniques and applications

Backwards and superluminal propagation are strongly counterintuitive, but are fully explained by standard physics.

# Special Thanks to My Students and Research Associates



# Thank you for your attention!