Slow, Fast, and “Backwards” Light: Fundamentals and Applications

Robert W. Boyd

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

www.optics.rochester.edu/~boyd

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

Presented at Australian Universities and OSA Student Chapters, June and July 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

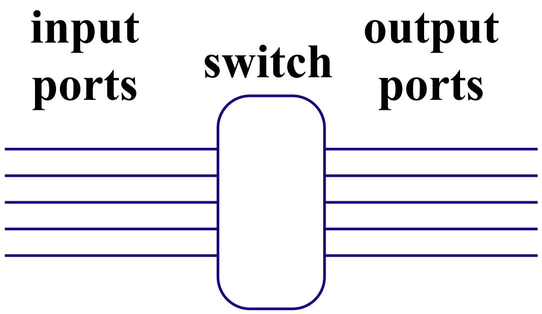
Implications for quantum information

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

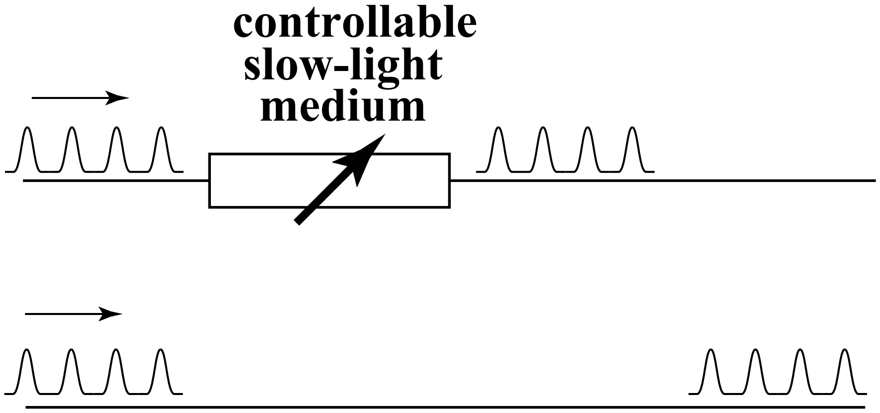
Boyd and Gauthier, “Slow and Fast Light,” in Progress in Optics, 43, 2002.

Slow Light and Optical Buffers

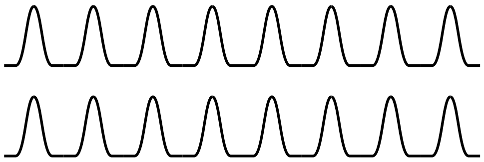
All-Optical Switch



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

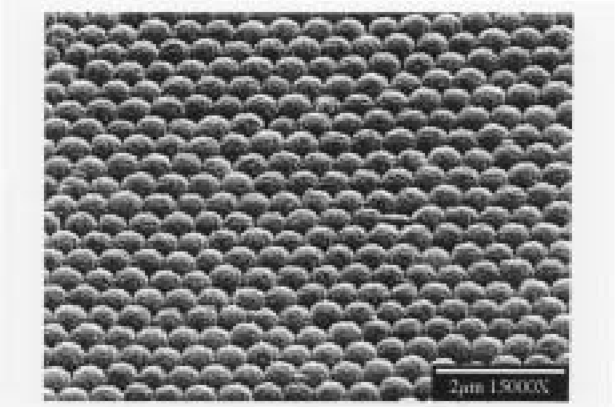
- Use the linear response of atomic systems

  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

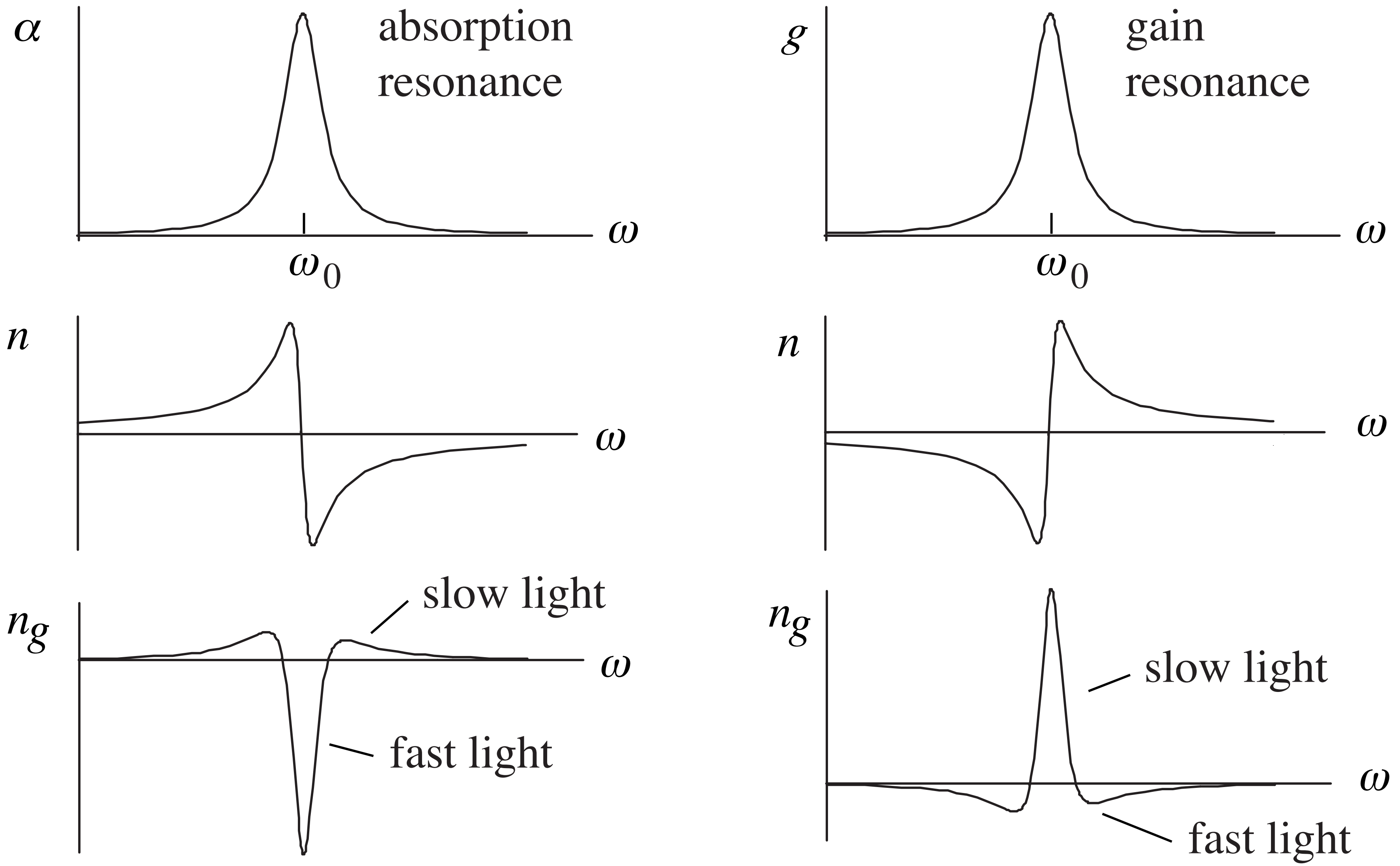
$$v_g = \frac{c}{n_g} \qquad\qquad n_g = n + \omega \frac{dn}{d\omega}$$

Want large dispersion to obtain extreme group velocities

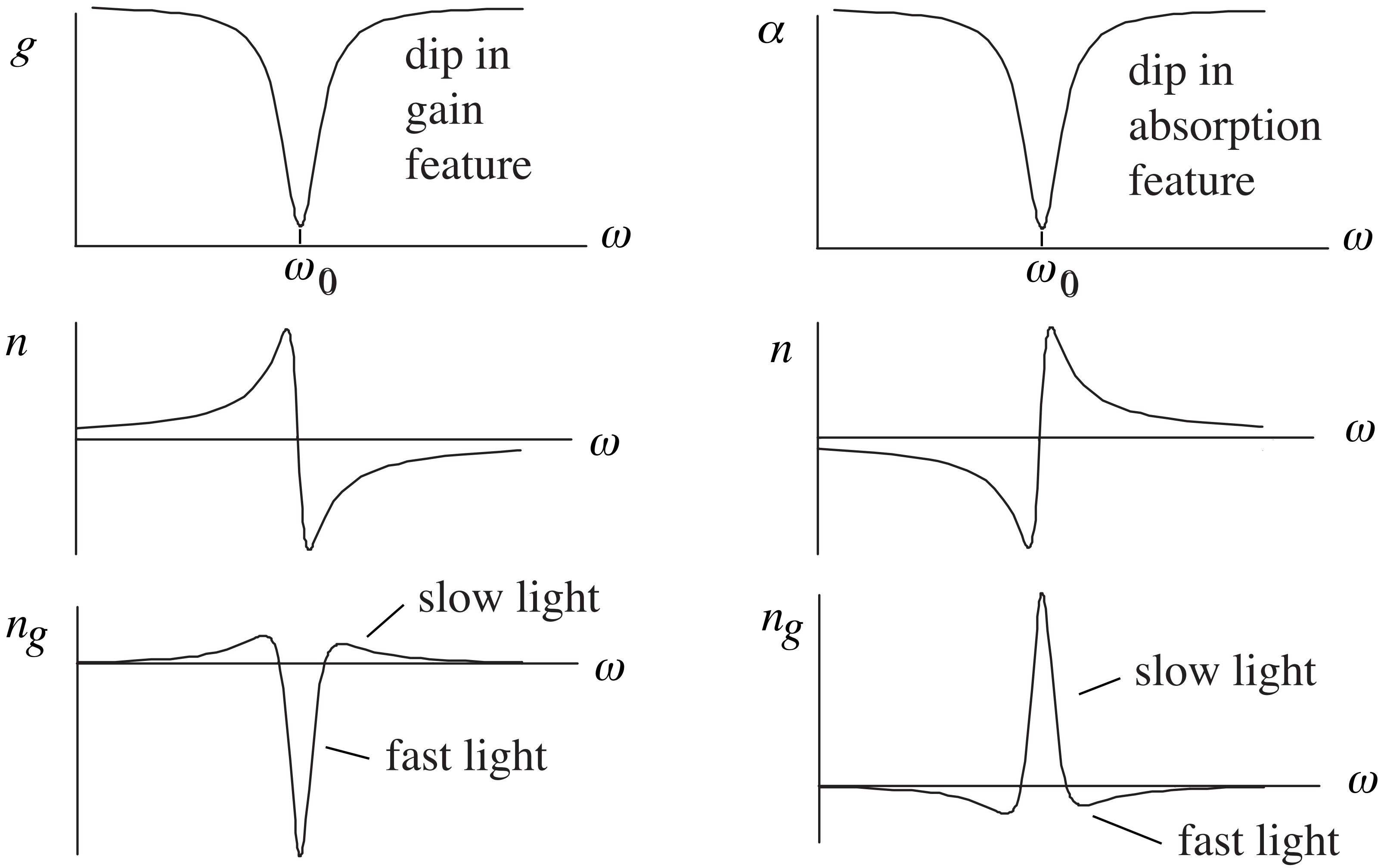
Sharp spectral features produce large dispersion.

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

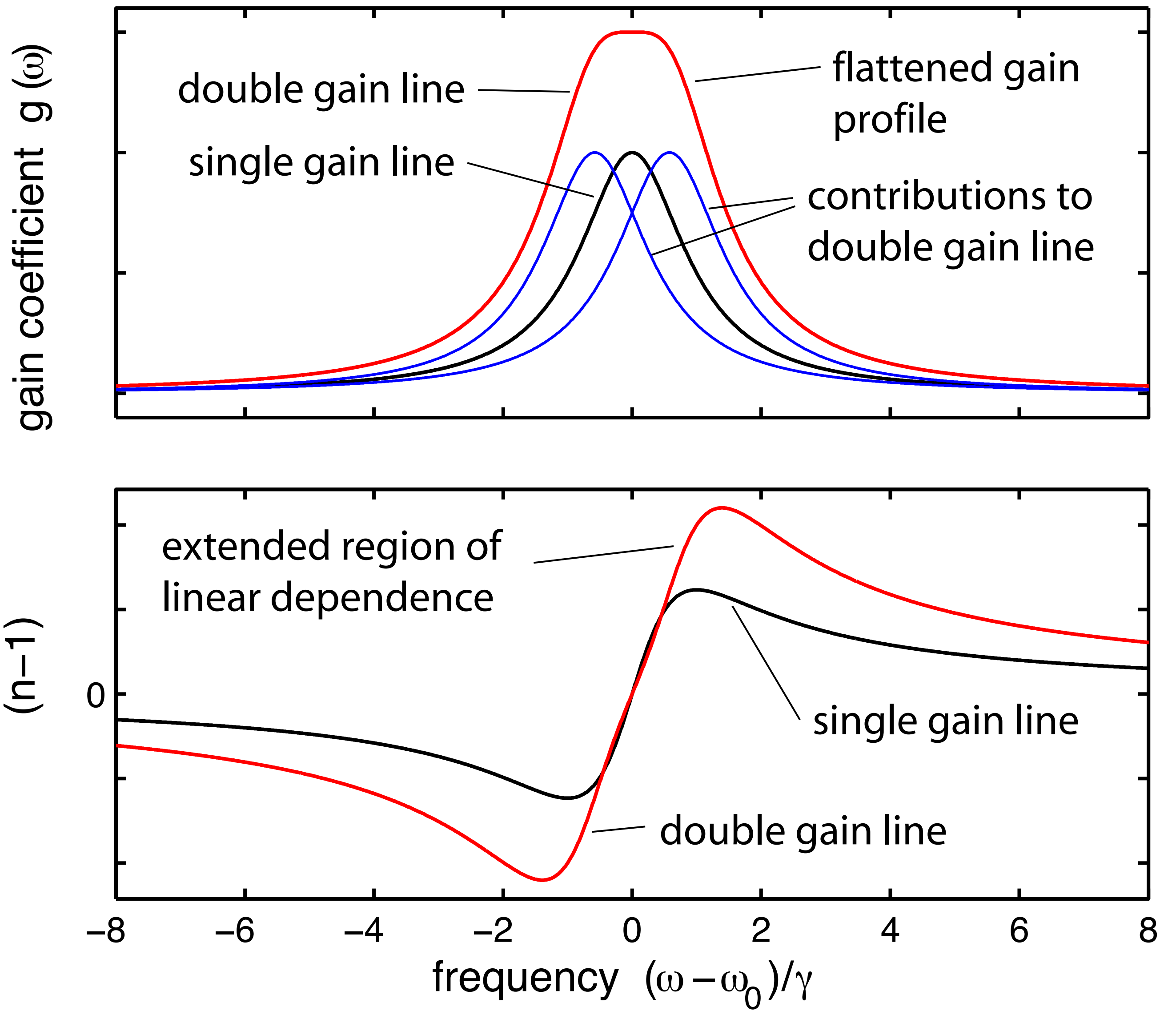


How to Create Slow and Fast Light II – Use Dip in Gain or Absorption Feature



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 – Dispersion Management



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

Dispersion of Water Waves

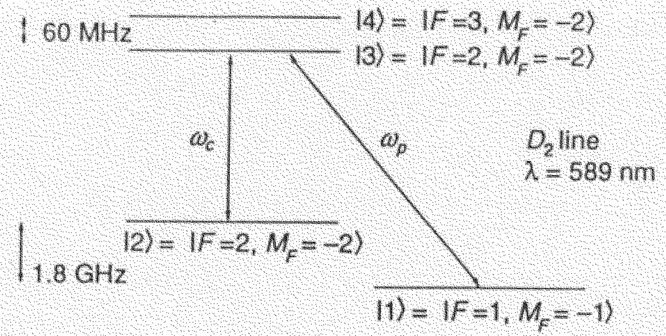
* from F. Bitter and H. Medicus, Fields and particles; an introduction to electromagnetic wave phenomena and quantum physics

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

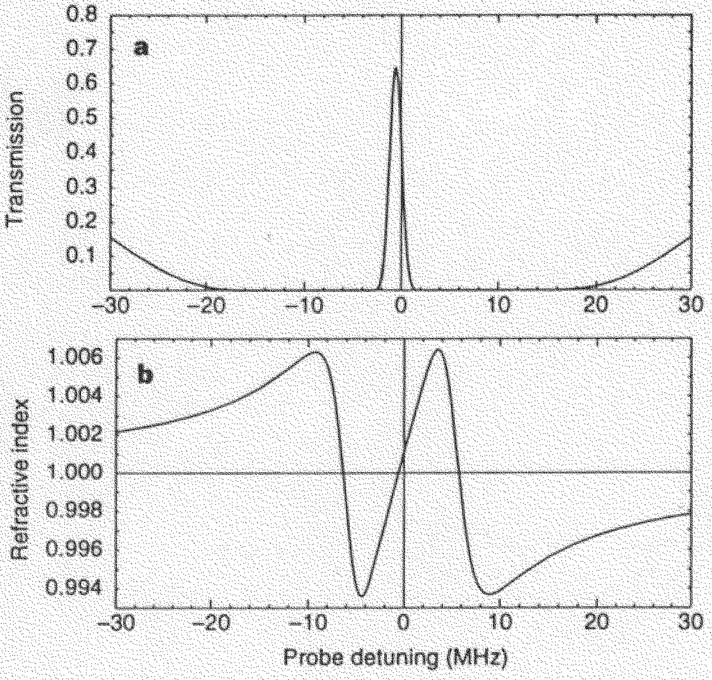
Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§

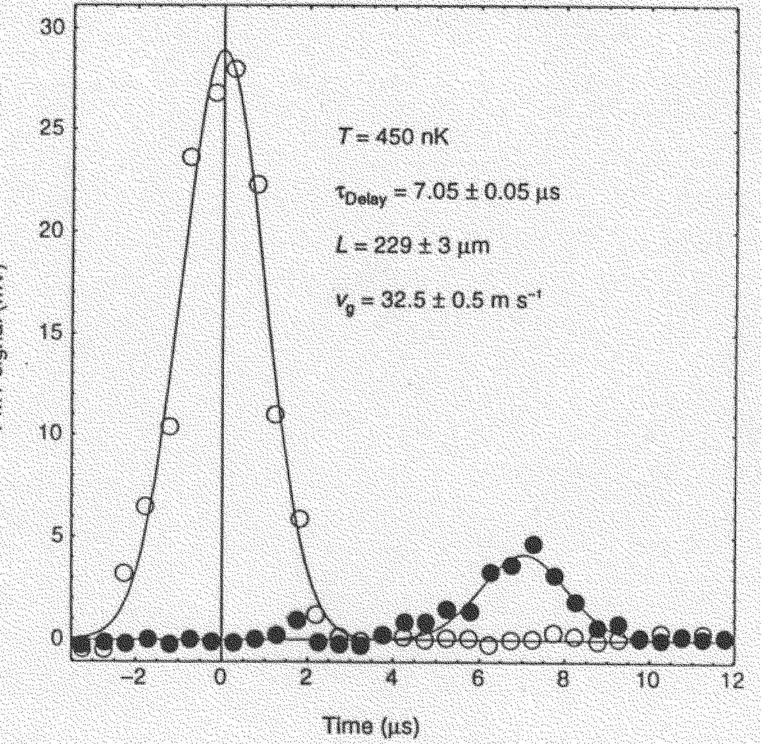
* *Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142, USA*
† *Department of Physics,* § *Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*
‡ *Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

Nature, 397, 594, (1999).



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



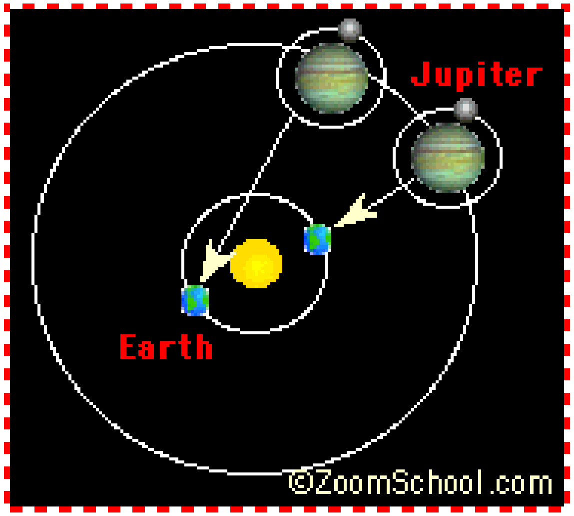


Determination of the Velocity of Light*

"Astronomical" Methods

Rømer (1676) First evidence that velocity of light is finite!

Observed an apparent variation of up to 22 minutes in the orbital period of the satellite Io in its orbit about Jupiter.



Deduced that c = 225,000 km/sec

(Actually, light transit time from sun to earth is just over 8 minutes, and c = 299,793 km/sec)

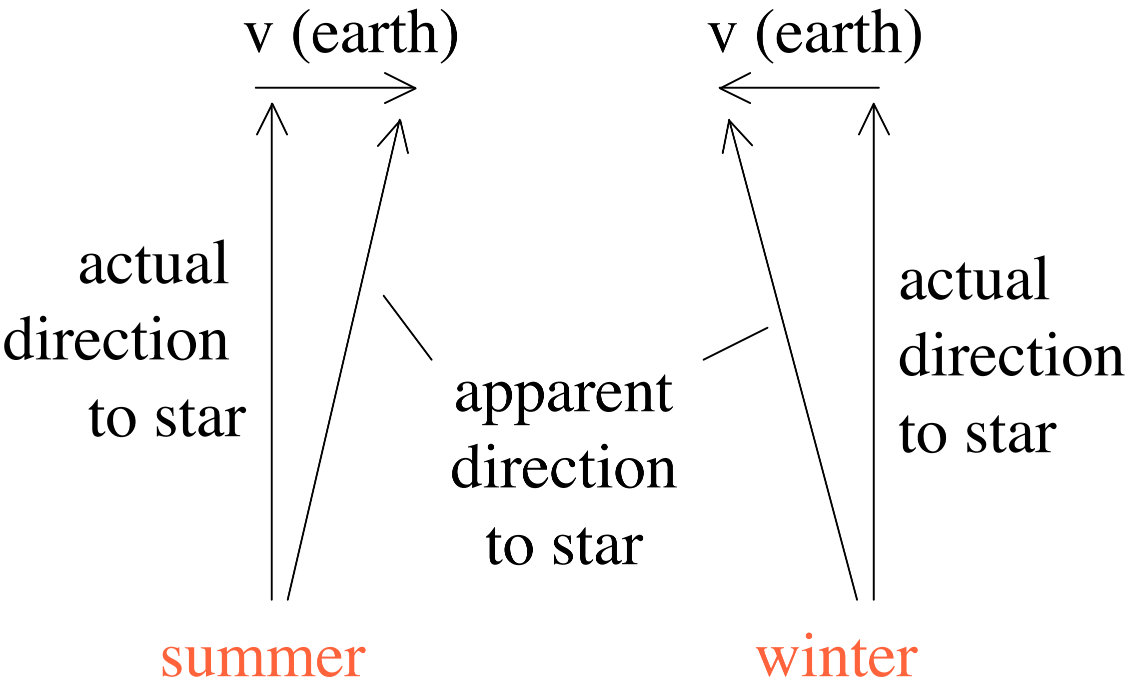
*See, for instance, Jenkins and White, 1976.

Determination of the Velocity of Light

Astronomical Methods

Bradley (1727); Aberration of star light.

Confirmation of the finite velocity of light.



v (earth)

v (earth)

actual direction to star

apparent direction to star

actual direction to star

summer

winter

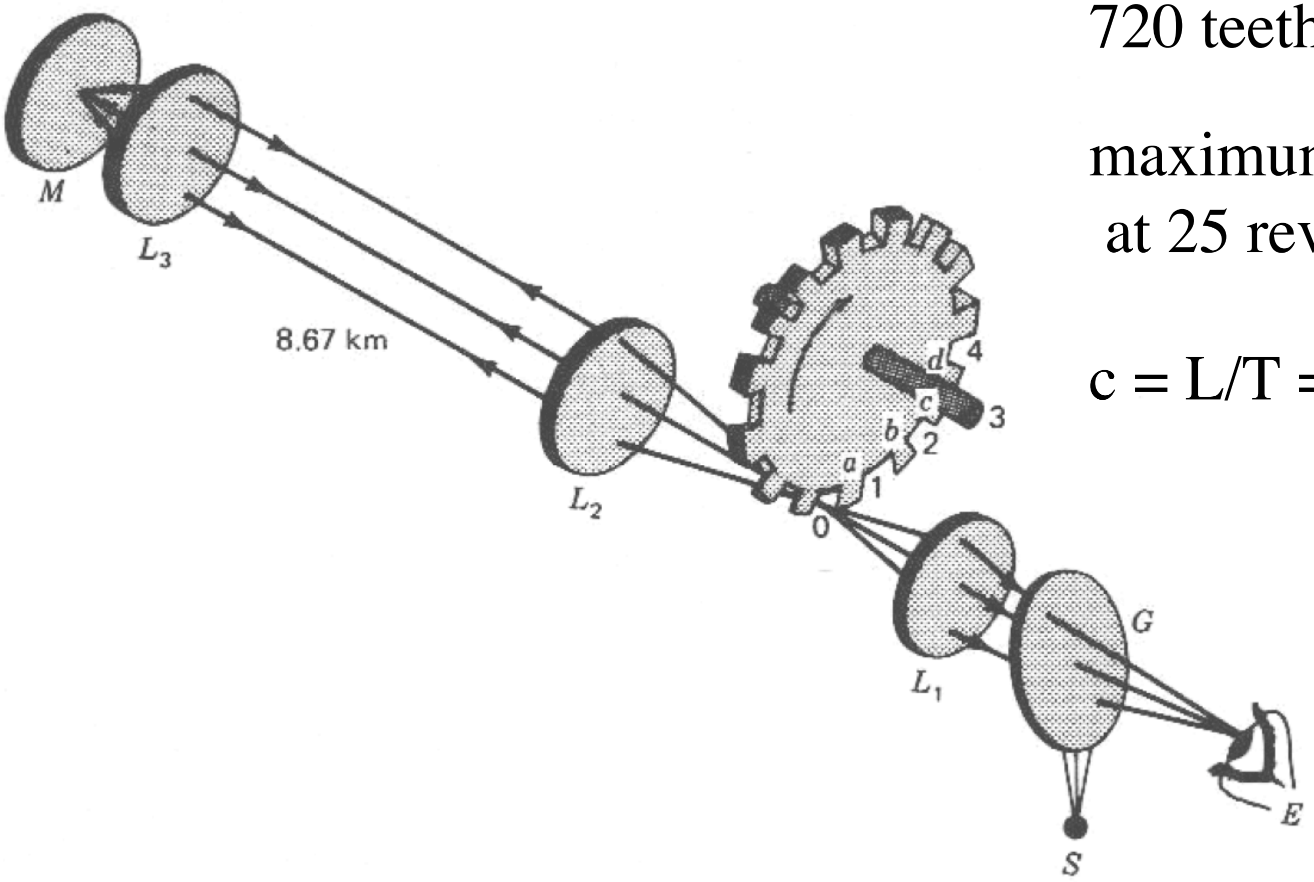
$$v(\text{earth}) \approx 30 \text{ km/s}$$

$$\tan\alpha = \frac{v(\text{earth})}{c}$$

$$\alpha = 20.5 \text{ arcsec}$$

Determination of the Velocity of Light
Laboratory Methods

Fizeau (1849) Time-of-flight method



720 teeth in wheel

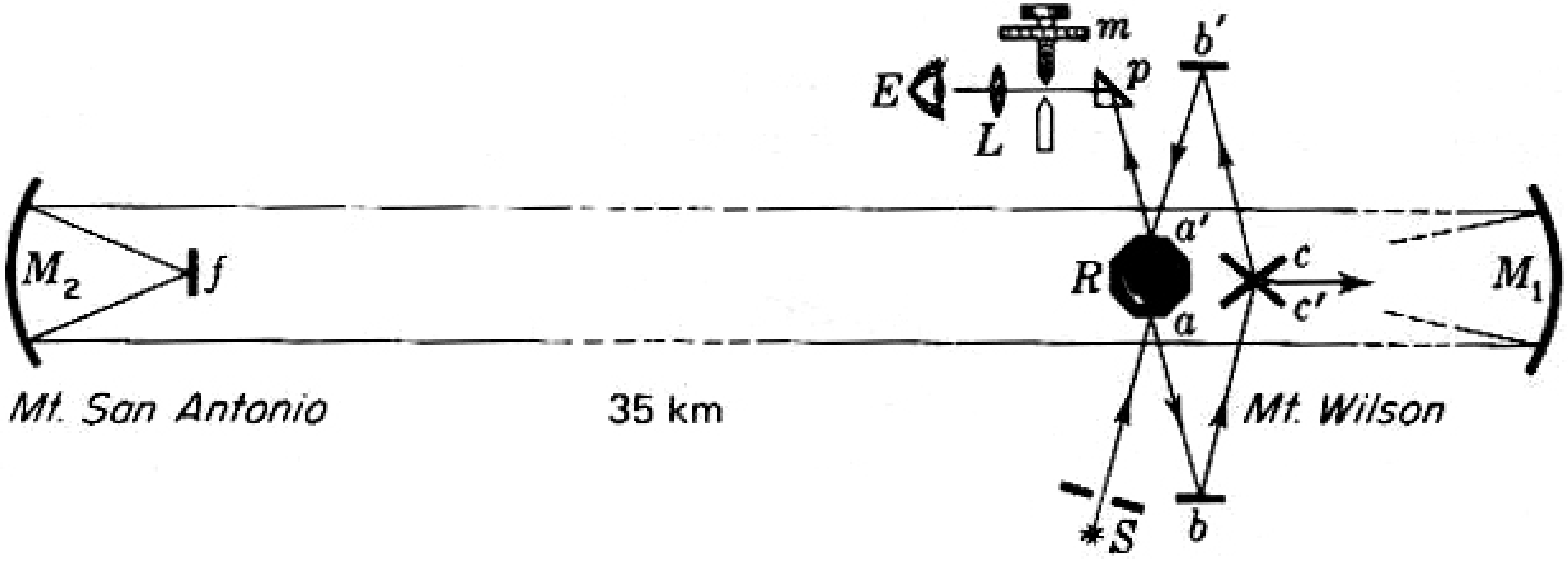
maximum transmission
at 25 revolutions/sec

c = L/T = 320,000 km/s

Determination of the Velocity of Light

Laboratory Methods

Michelson (1926); Improved time of flight method.



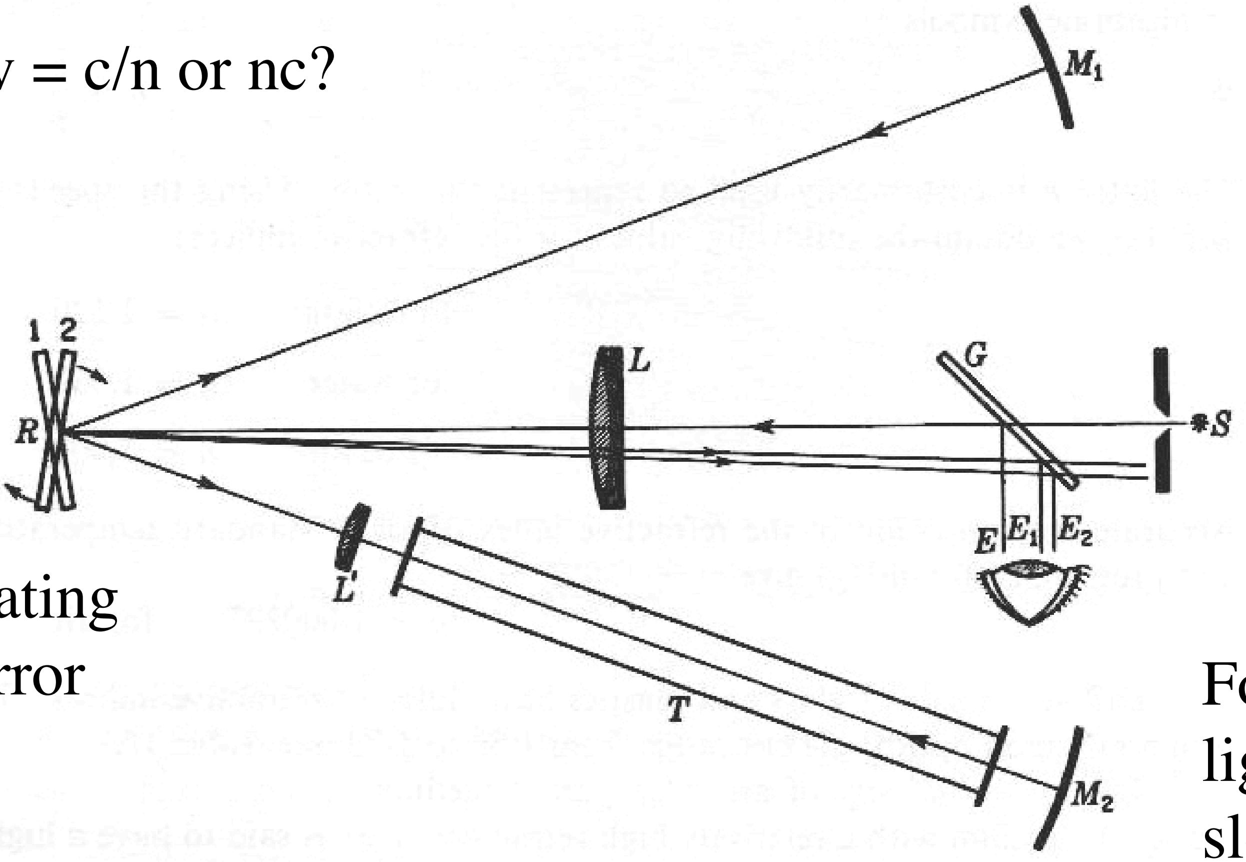
Rotating octagonal mirror

c = 299,796 km/s (or 299,798 km/s)

Velocity of Light in Matter

Foucault (1850) Velocity of light in water.

Is v = c/n or nc?



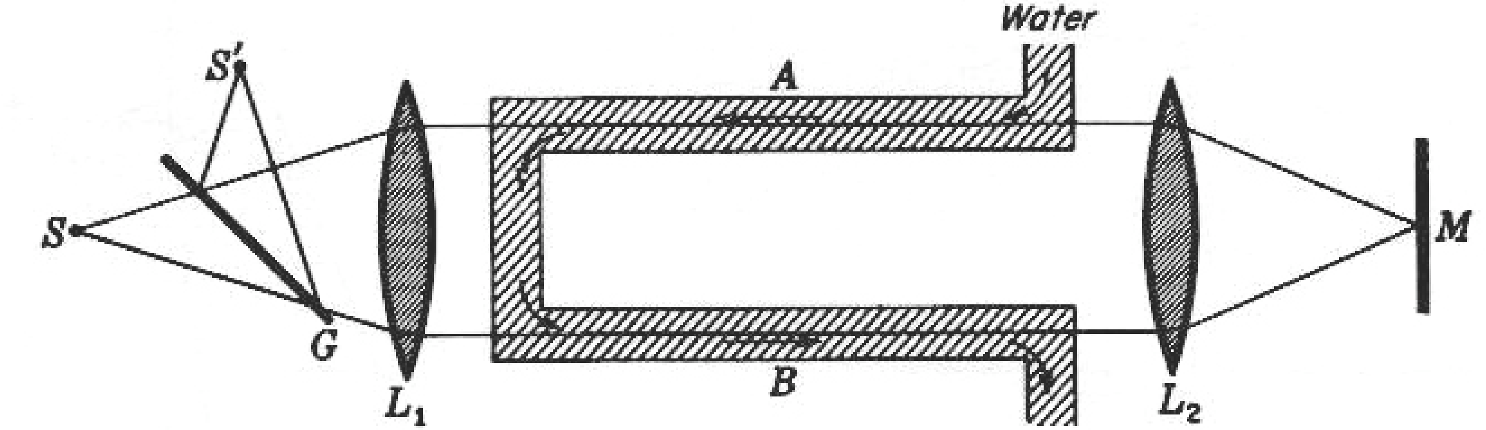
rotating
mirror

Foucault finds that
light travels more
slowly in water!

Velocity of Light in Moving Matter

Fizeau (1859); Velocity of light in flowing water.

V = 700 cm/sec; L = 150 cm; displacement of 0.5 fringe.

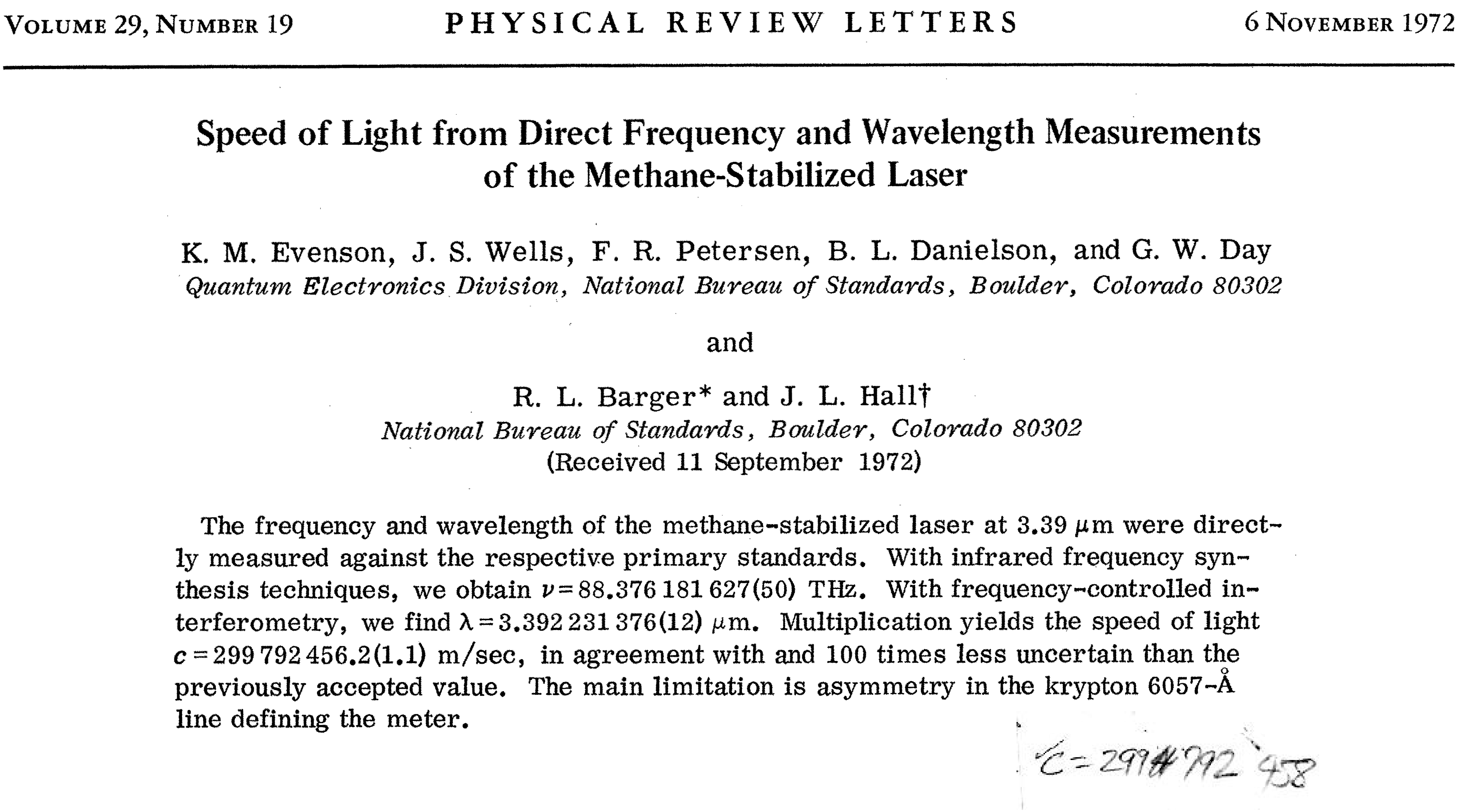


Modern theory: relativistic addition of velocities

$$v = \frac{c/n + V}{1 + (V/c)(1/n)} \approx \frac{c}{n} + V\left(1 - \frac{1}{n^2}\right)$$

Fresnel “drag” coefficient

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 μm 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 $\lambda = 3.392\,231\,376(12)$ μm. 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-Å line defining the meter.

c = 299 792 458

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

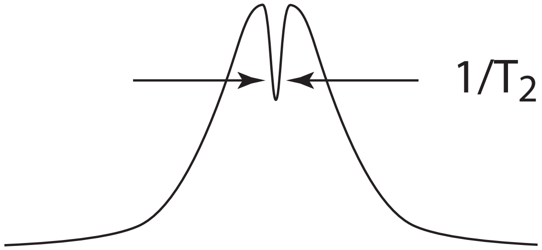
Recall that $n_g = n + \omega(dn/d\omega)$. Need a large $dn/d\omega$. (How?)

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

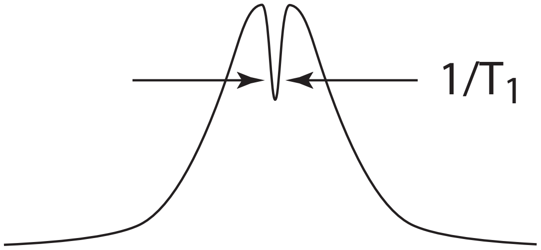
Well-known “trick” for doing so:

Make use of spectral holes due to population oscillations.

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



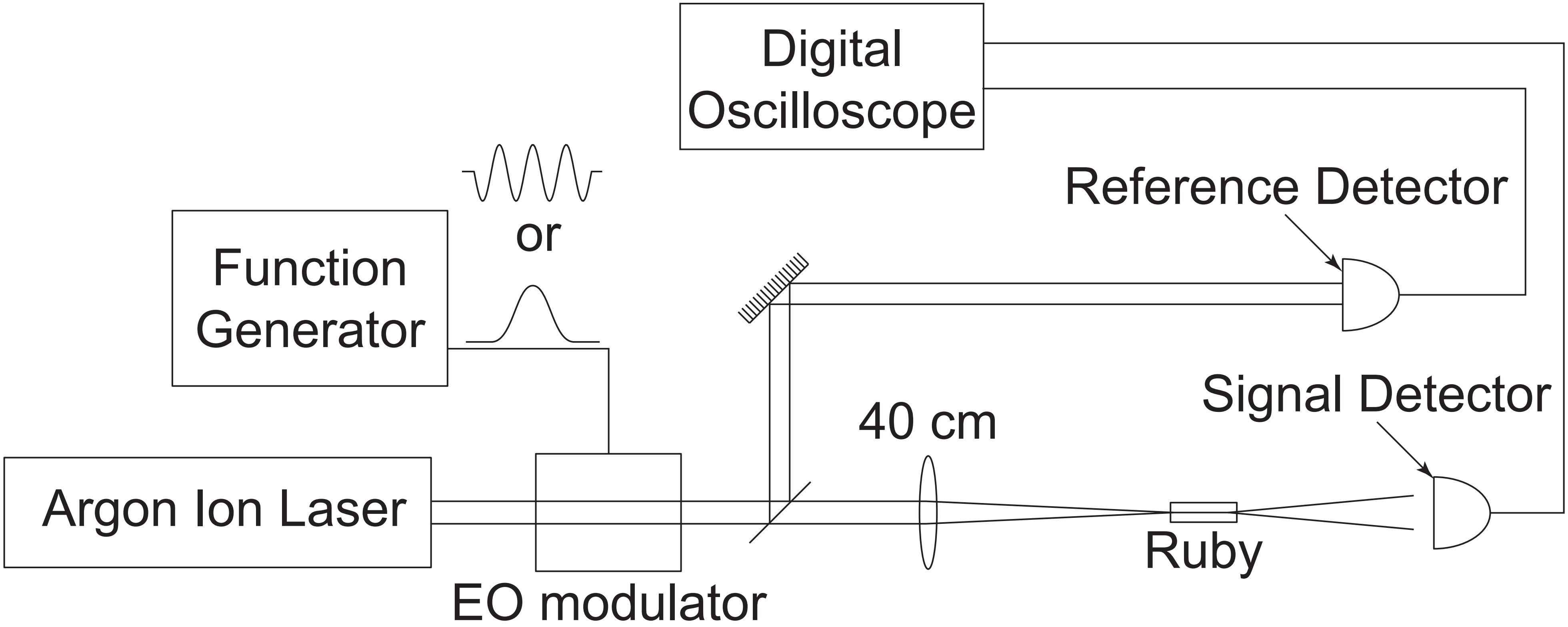
inhomogeneously
broadened medium



homogeneously
broadened medium
(or inhomogeneously
broadened)

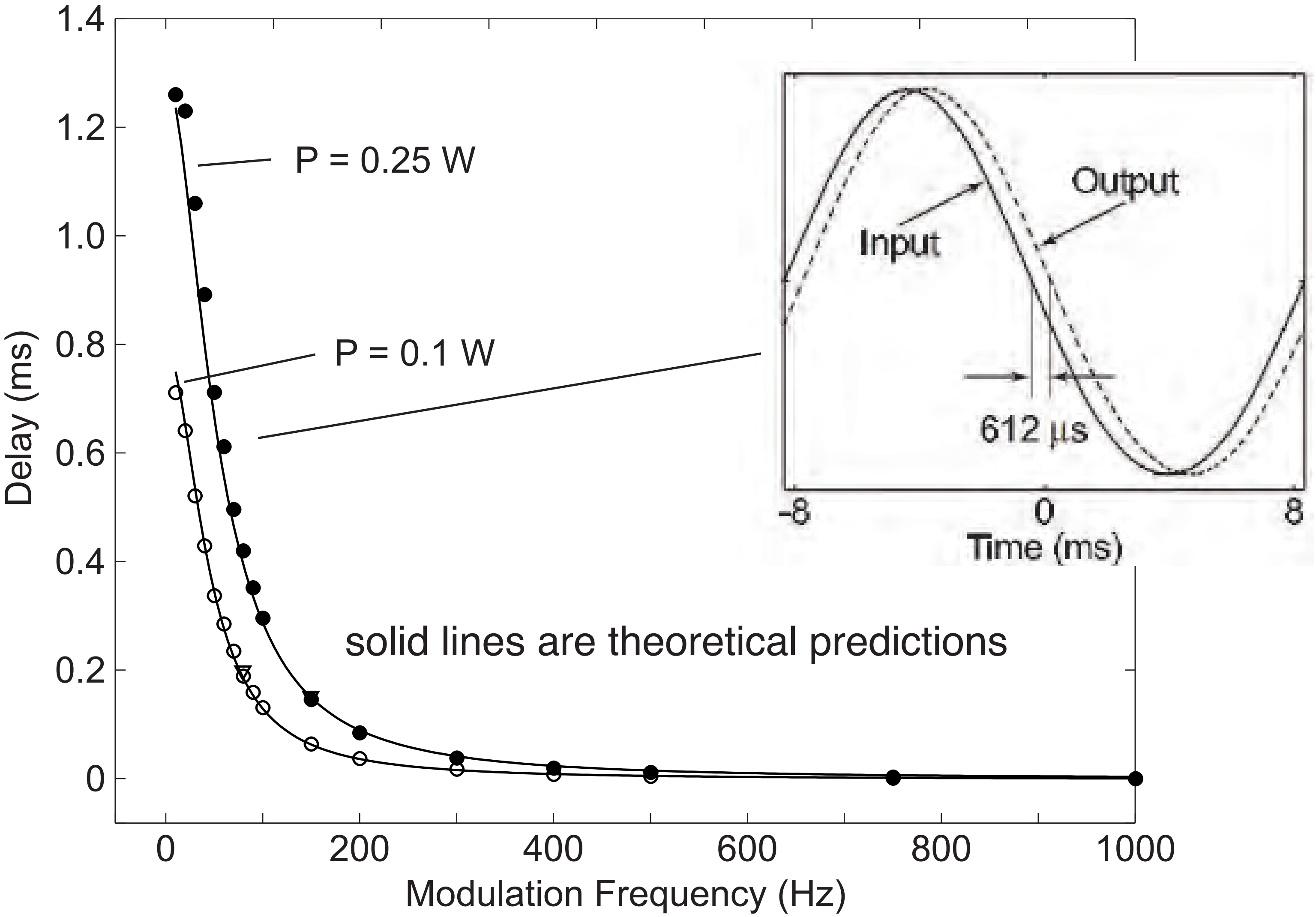
PRL 90,113903(2003).

Slow Light Experimental Setup



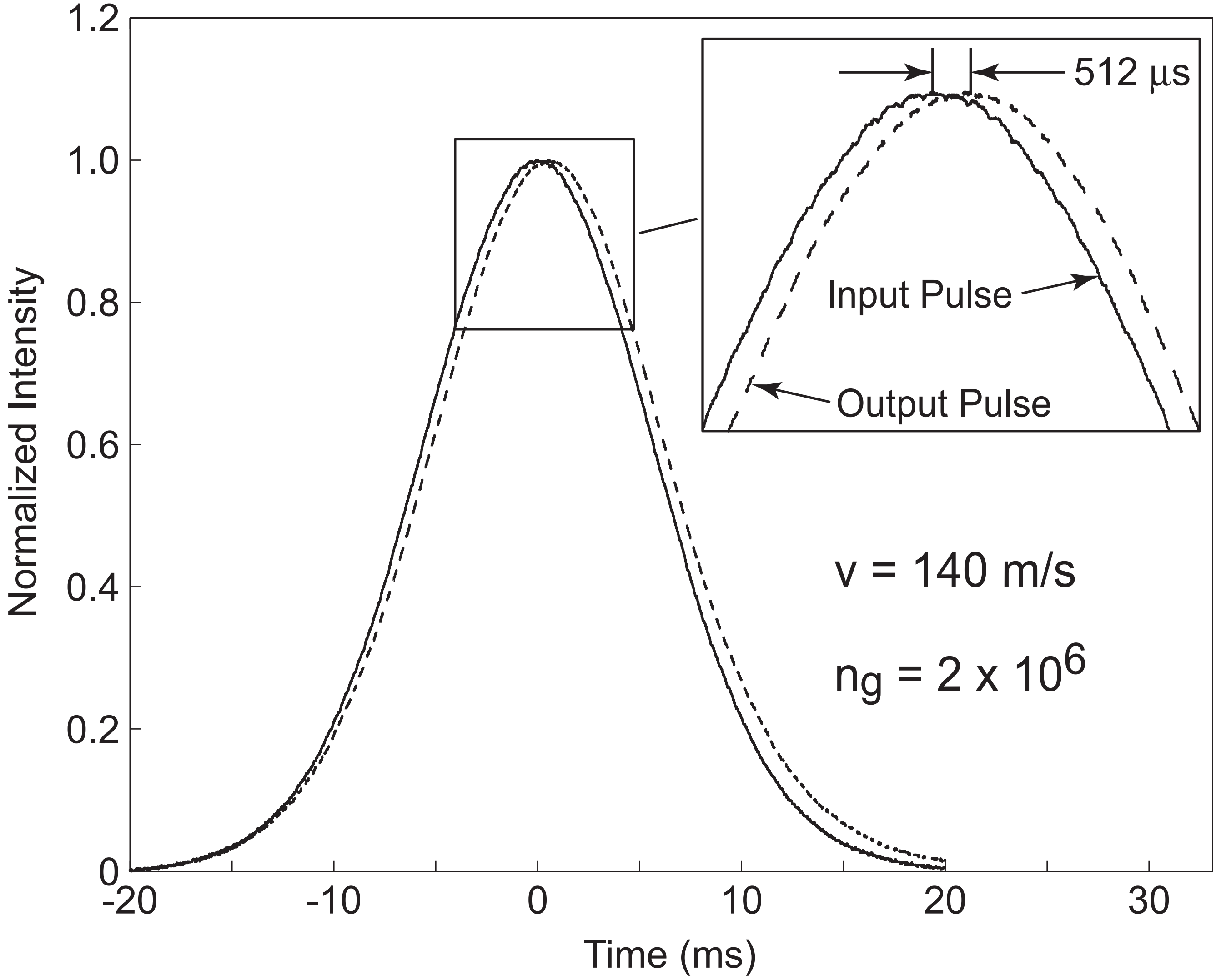
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



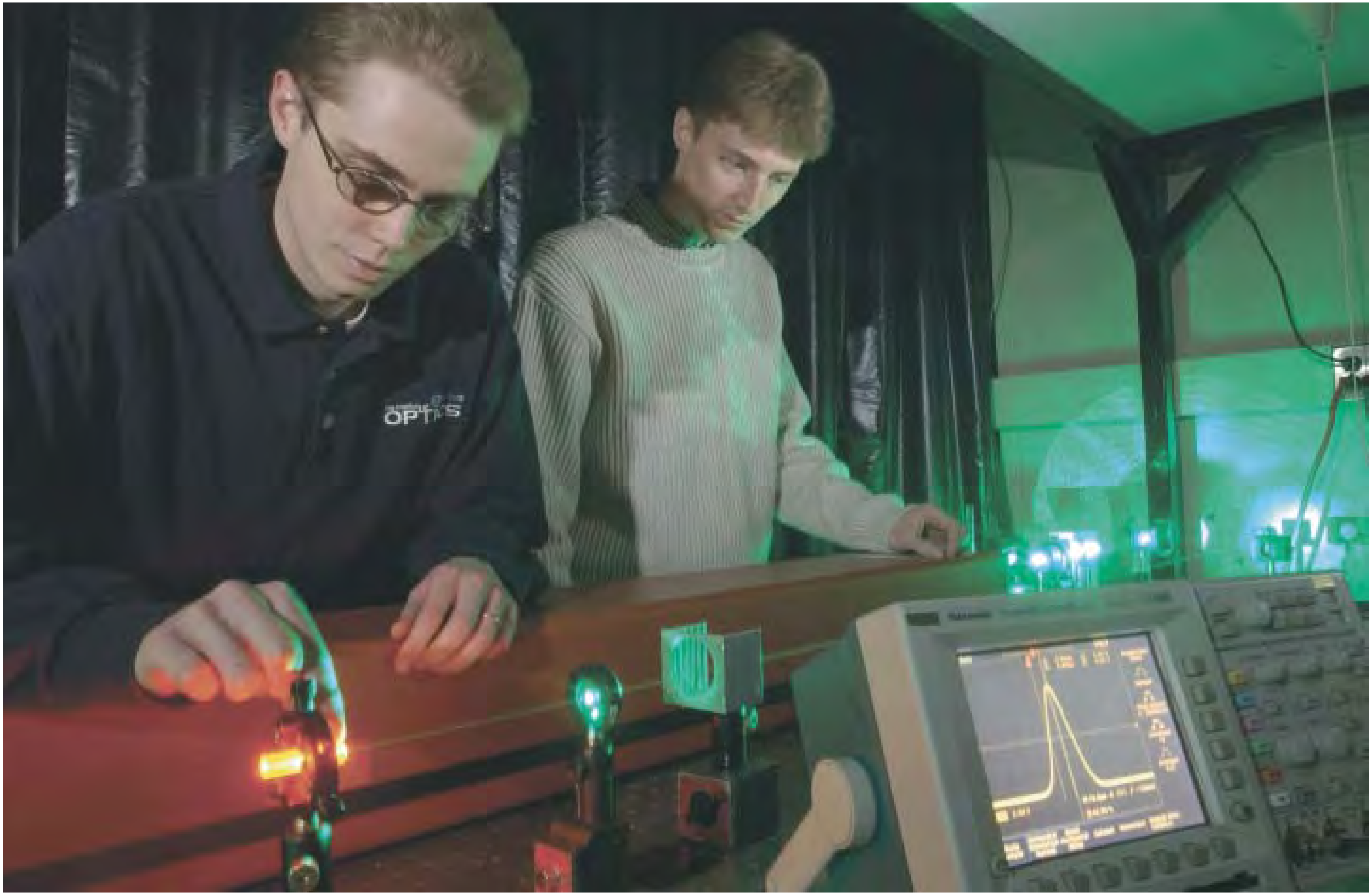
For 1.2 ms delay, $v = 60$ m/s and $n_g = 5 \times 10^6$

Gaussian Pulse Propagation Through Ruby



No pulse distortion!

Matt Bigelow and Nick Lepeshkin in the Lab



Advantages of Coherent Population Oscillations for Slow Light

Works in solids

Works at room temperature

Insensitive of dephasing processes

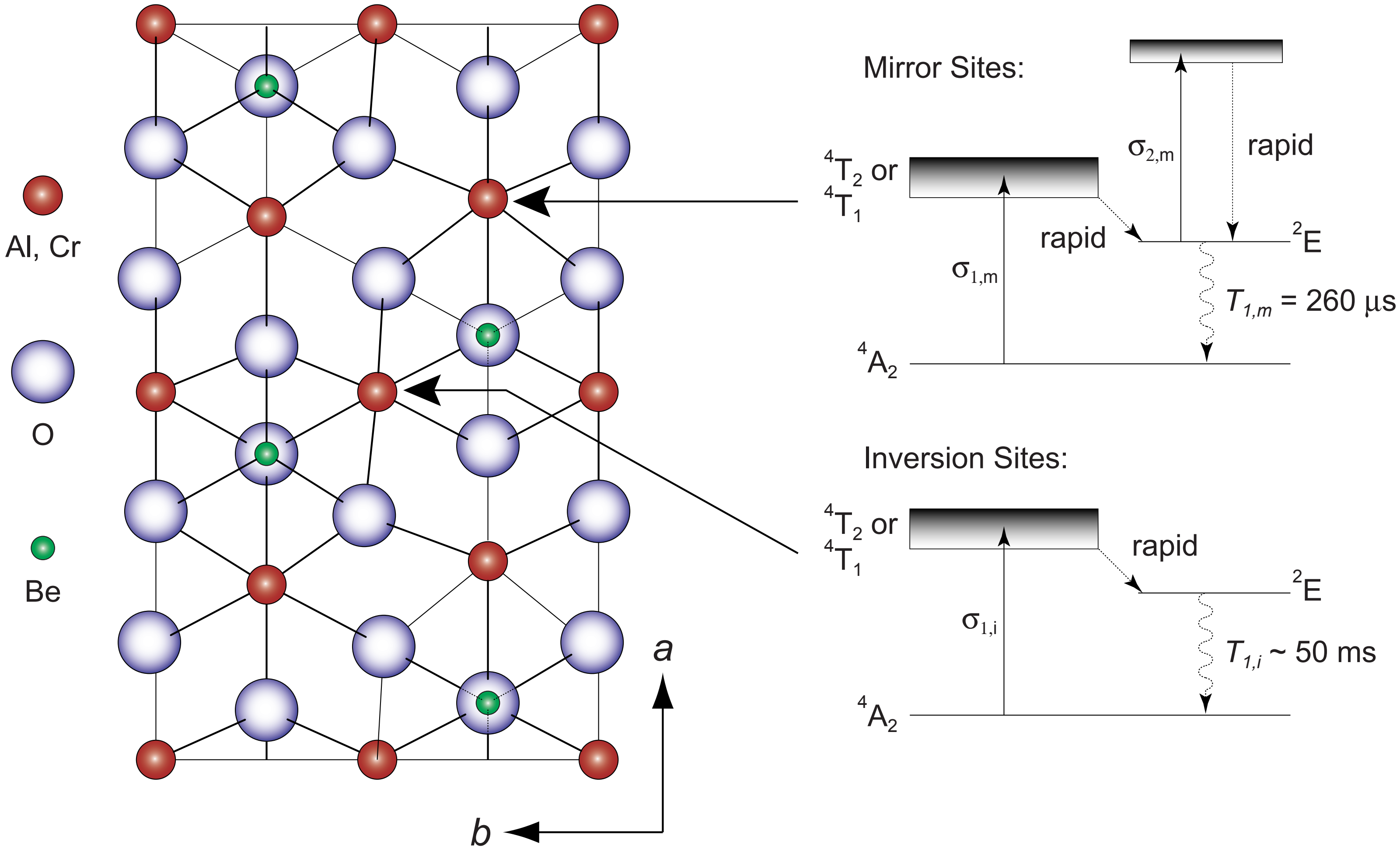
Laser need not be frequency stabilized

Works with single beam (self-delayed)

Delay can be controlled through input intensity

Alexandrite Displays both Saturable and Reverse-Saturable Absorption

- Both slow and fast propagation observed in alexandrite

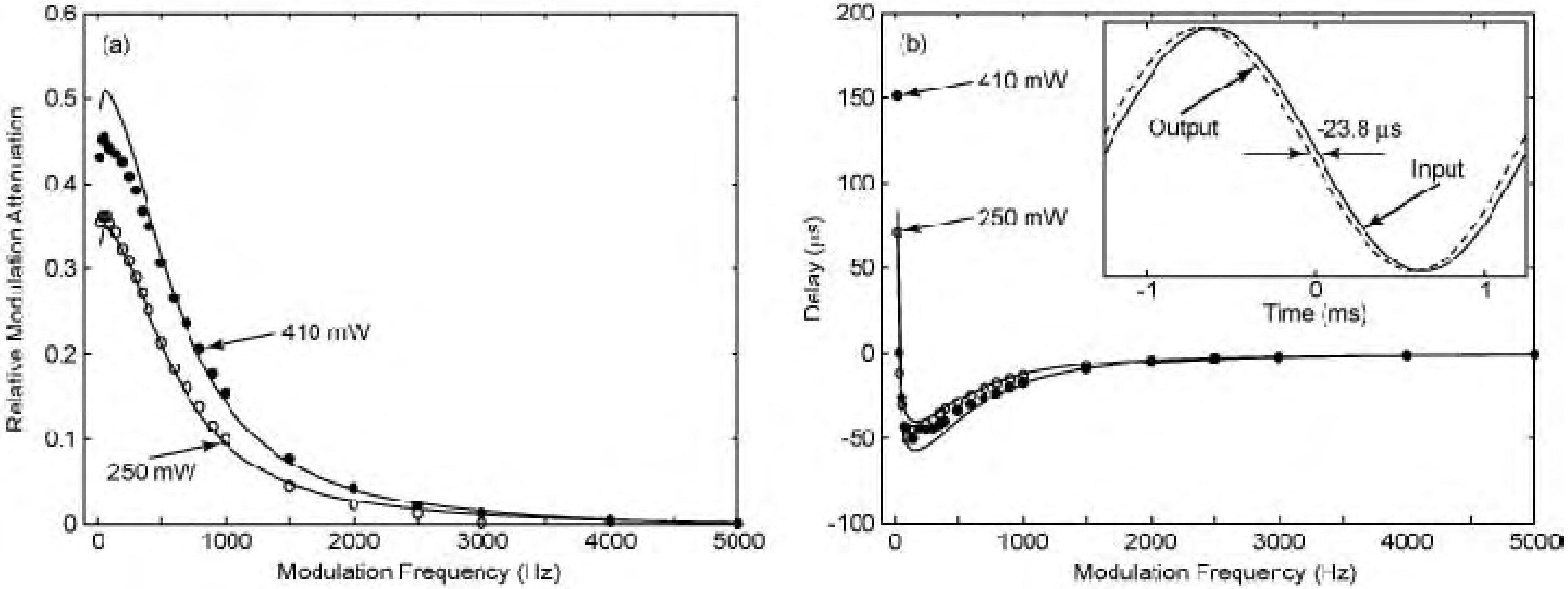


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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.

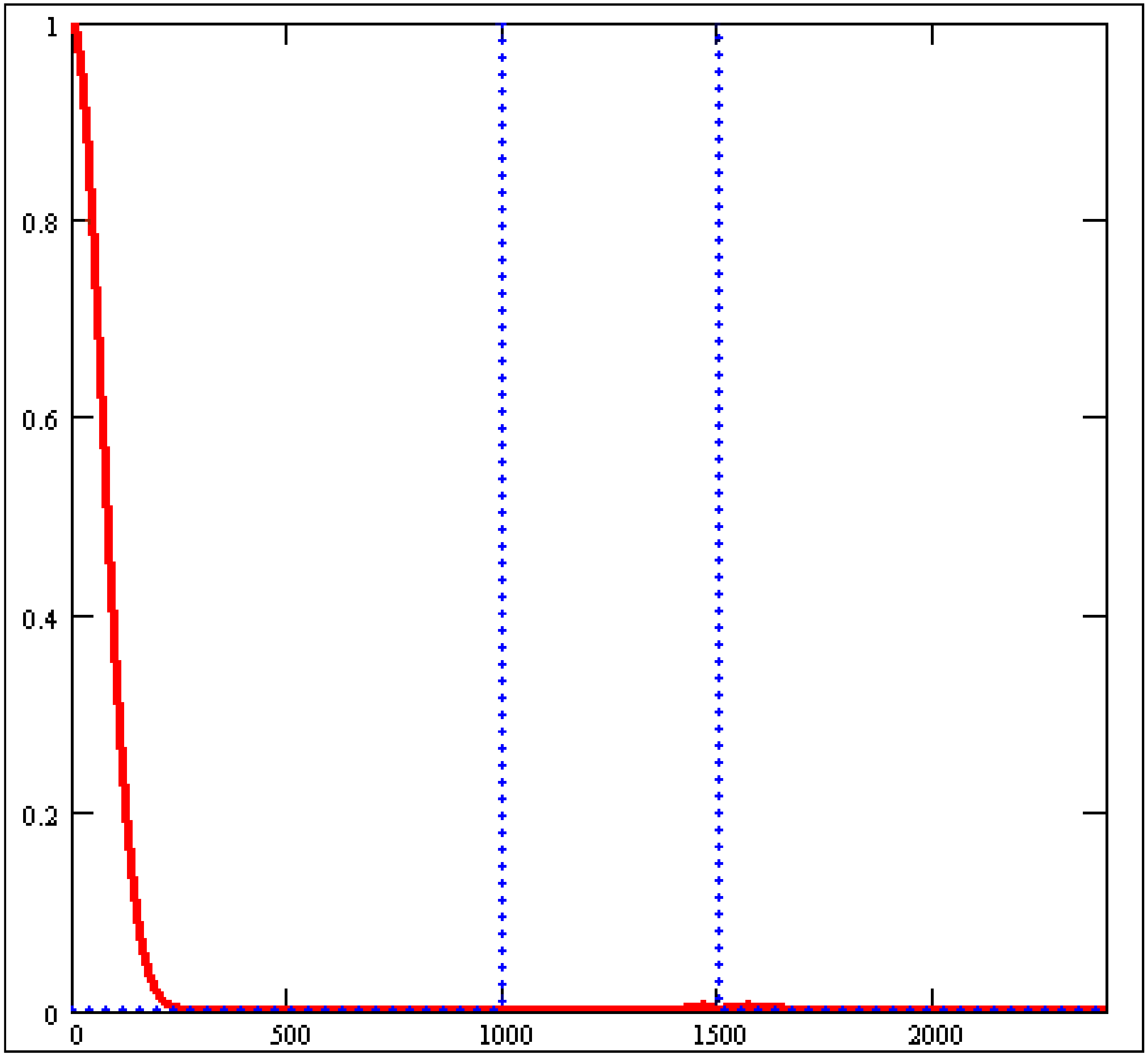
Study three cases:

Slow light $v_g = 0.5$ c

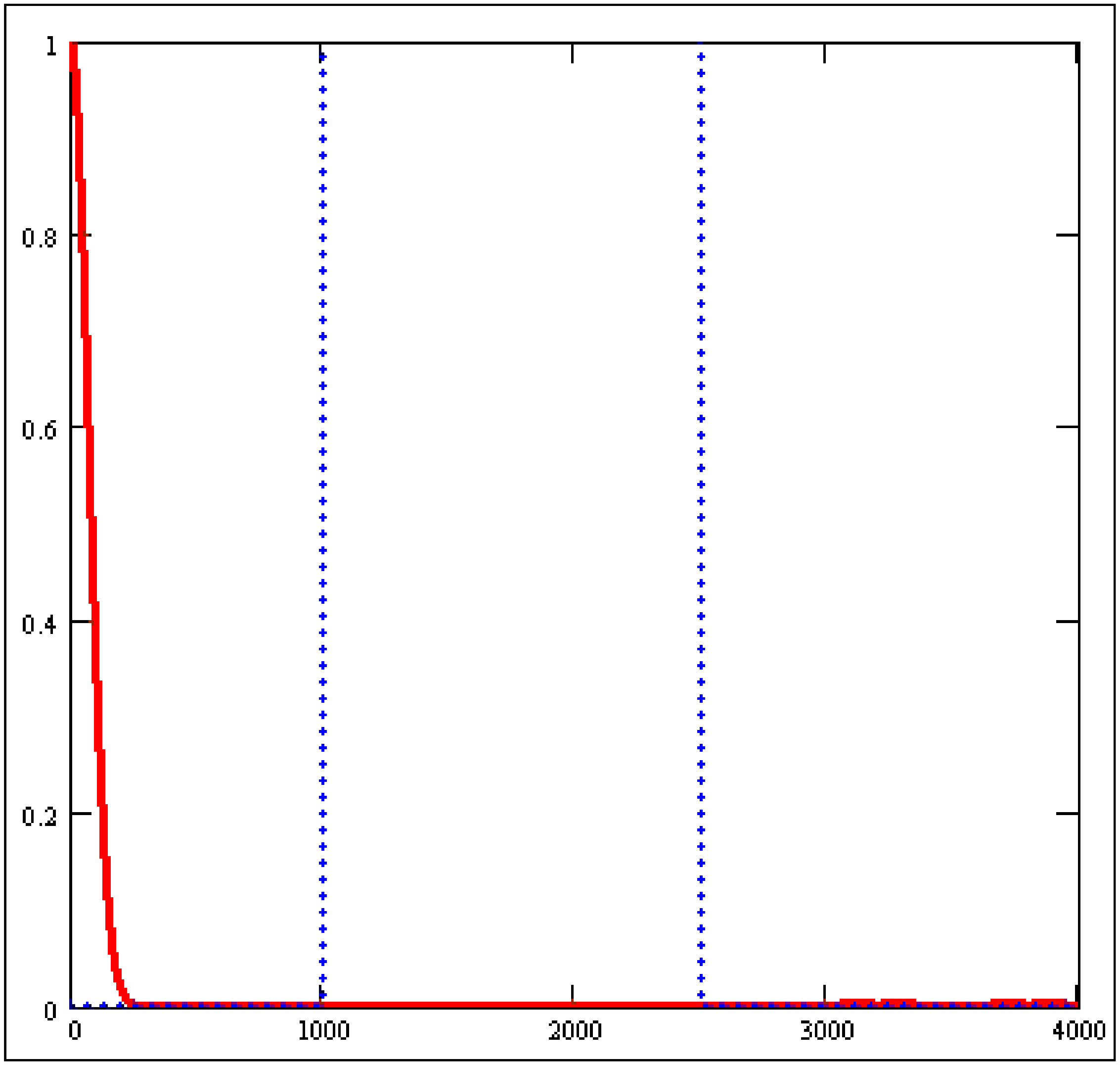
Fast light $v_g = 5$ c and $v_g = -2$ c

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

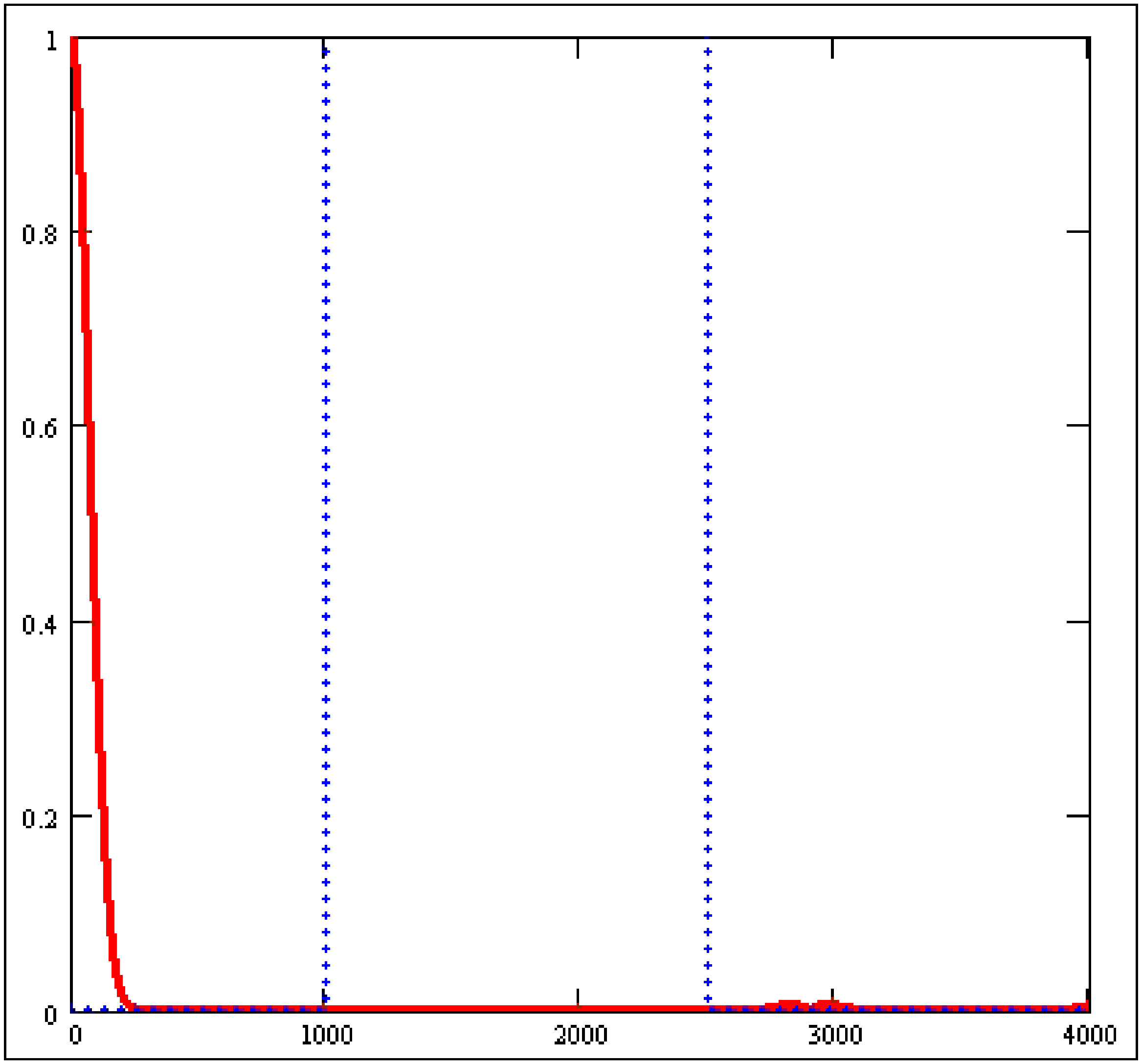
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



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

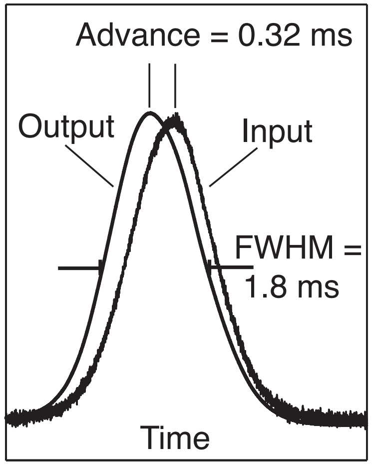


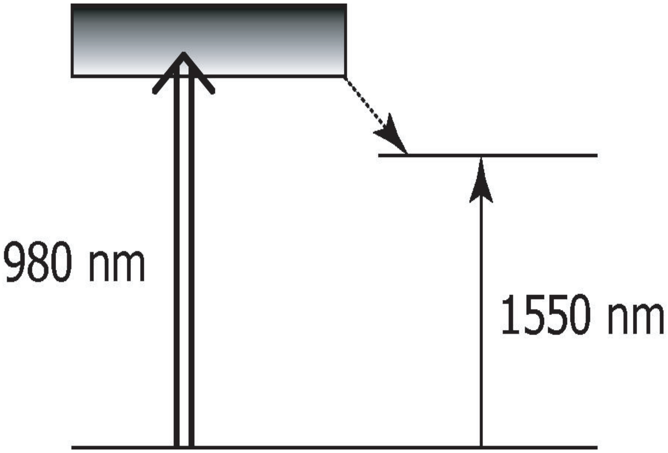
Pulse Propagation through a Fast-Light Medium (n_g = -.5, v_g = -2 c)

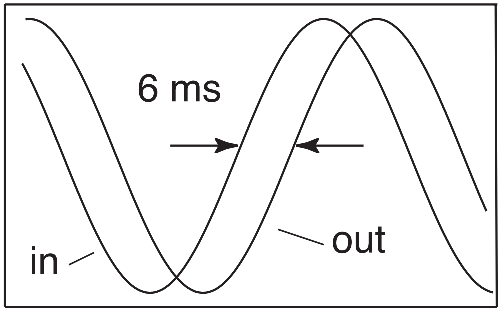


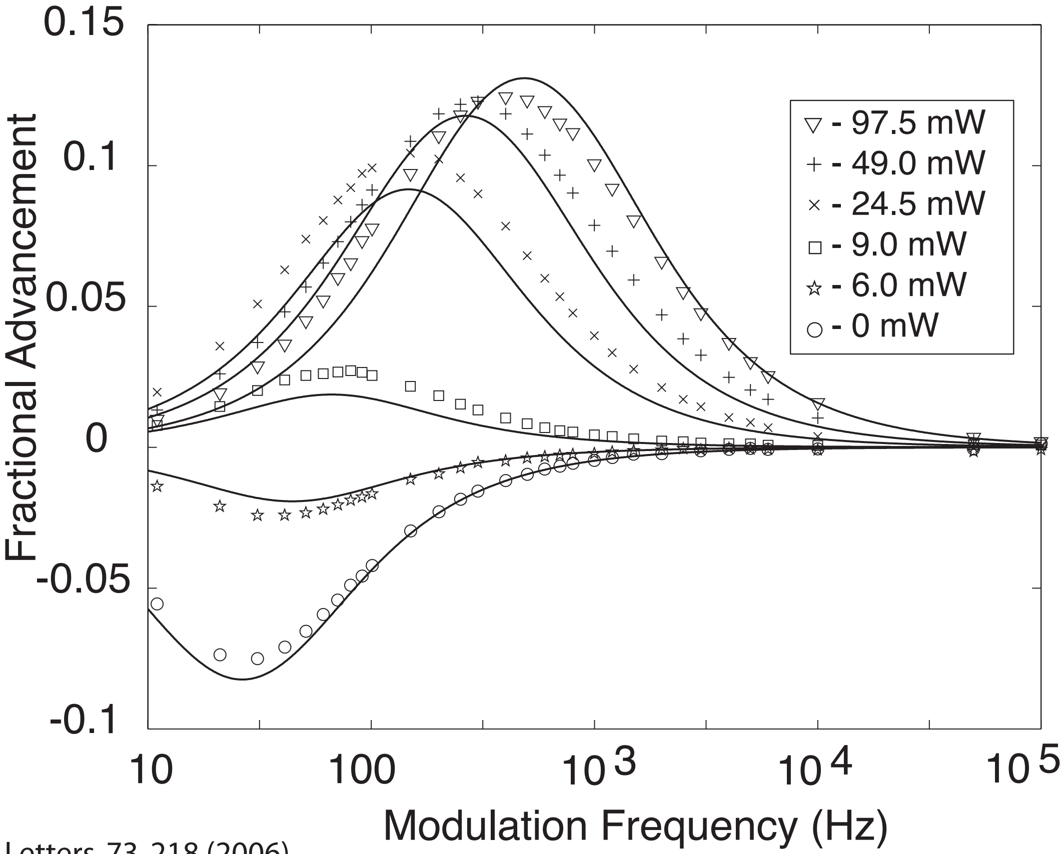
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



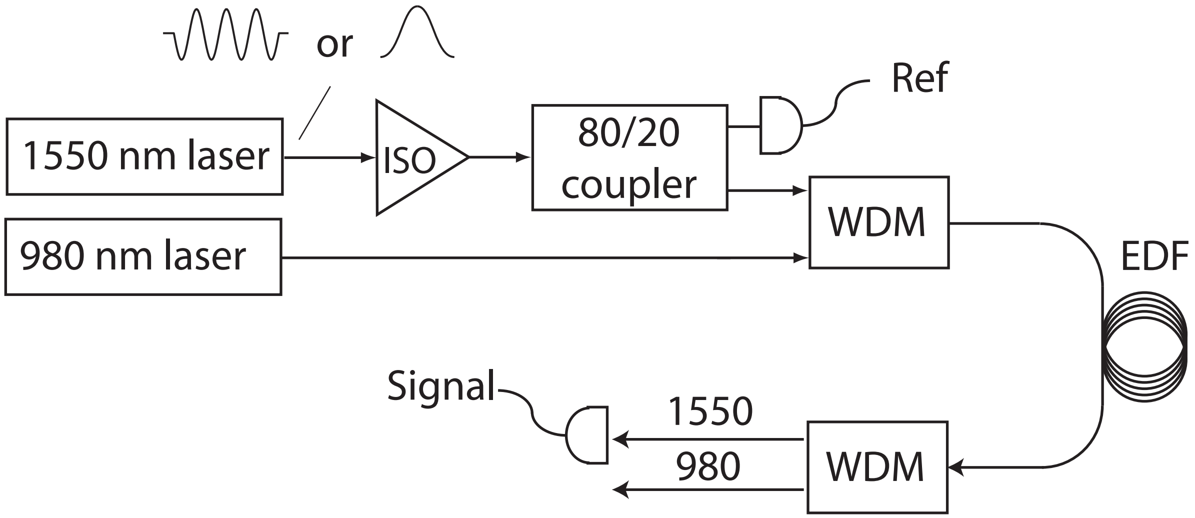






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

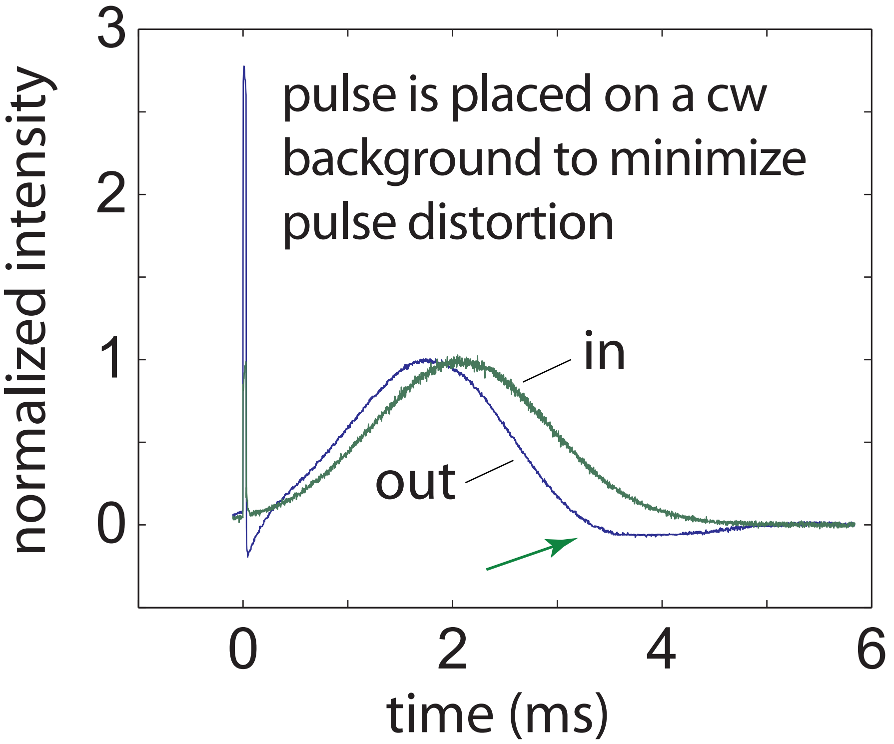
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



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

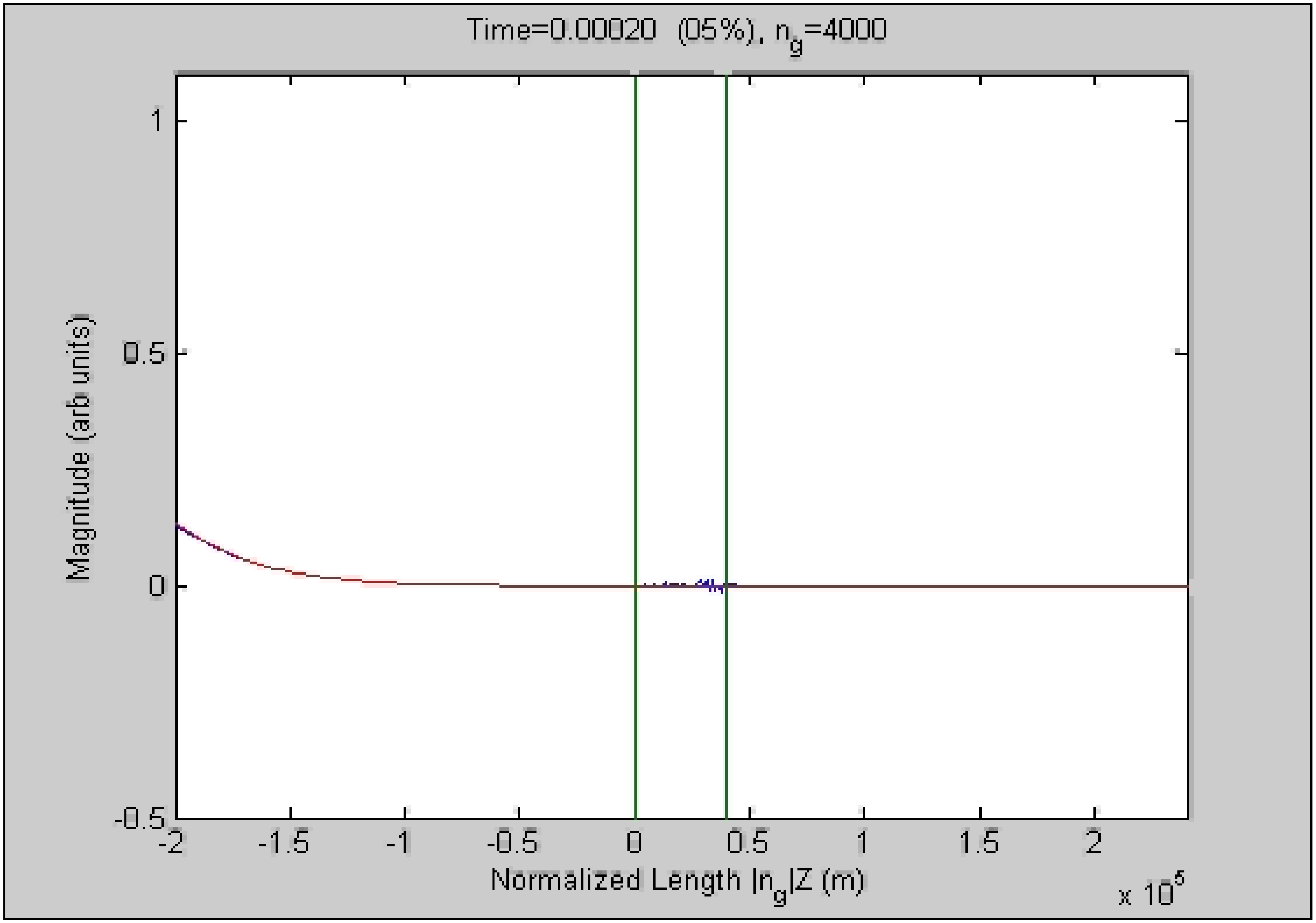


pulse is placed on a cw background to minimize pulse distortion

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

Experimental Results: Backward Propagation in Erbium-Doped Fiber

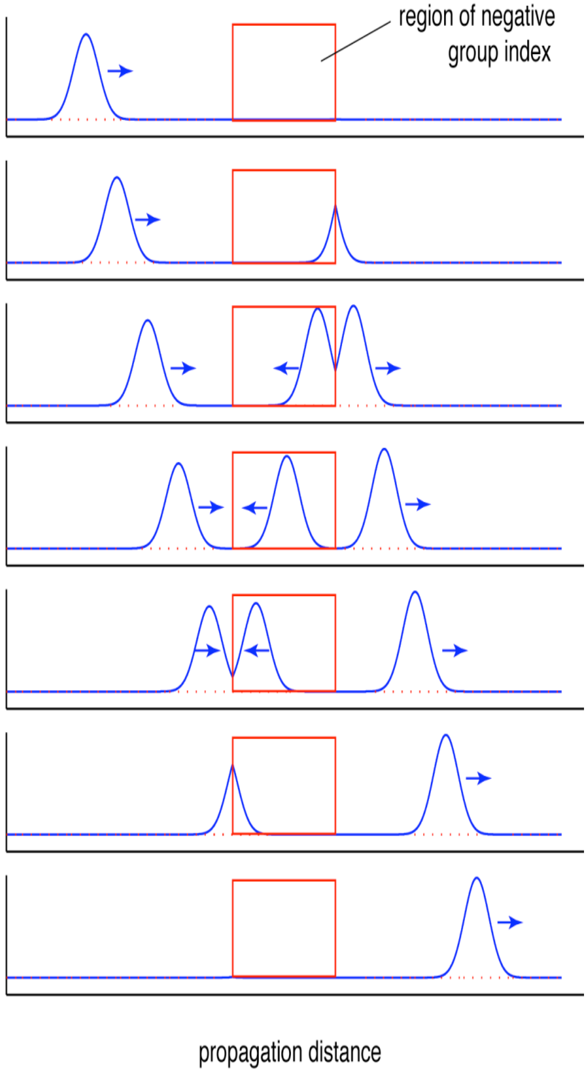
Normalized: (Amplification removed numerically)



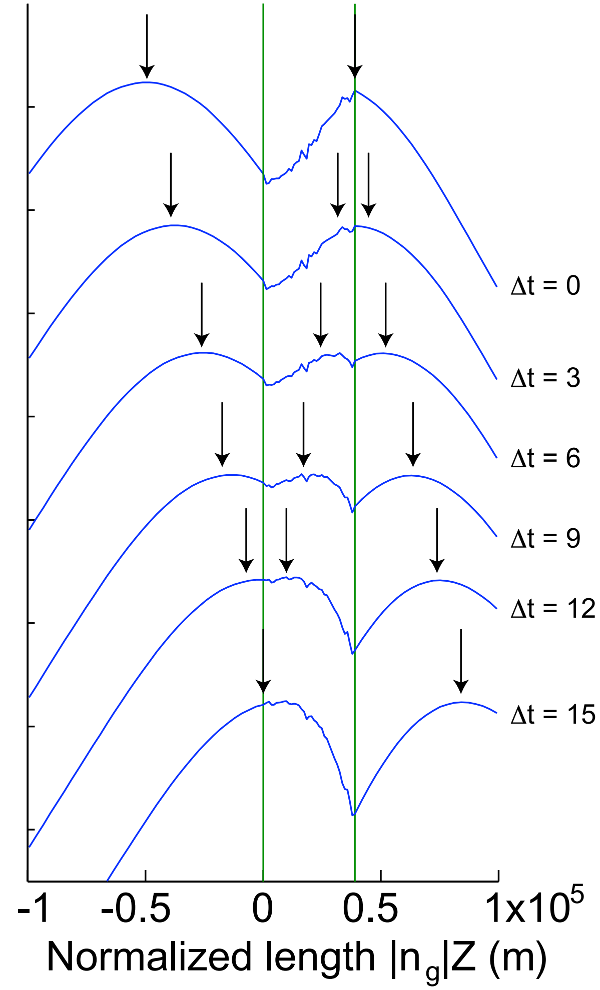
Observation of “Backwards” Pulse Propagation

- 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



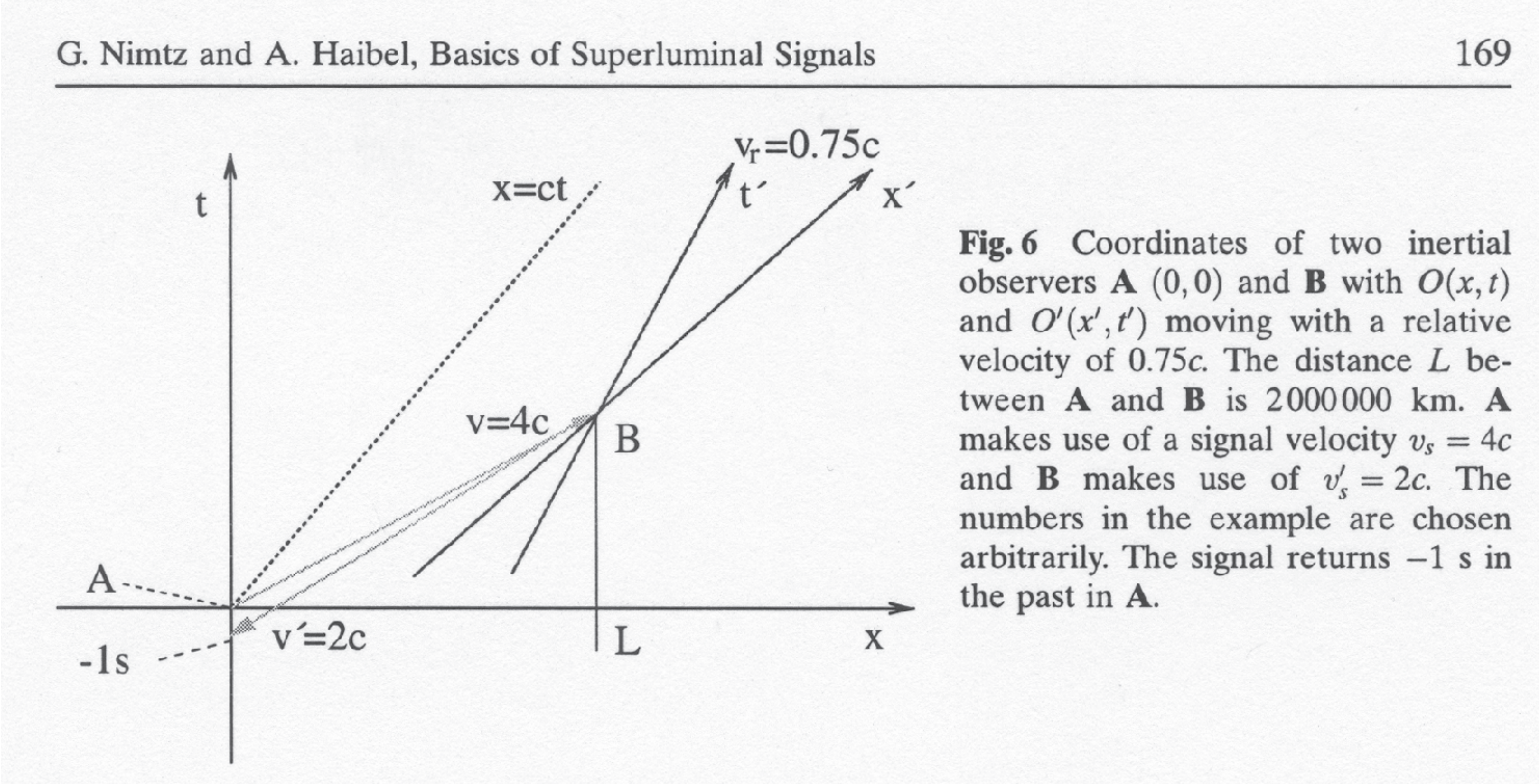
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier

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

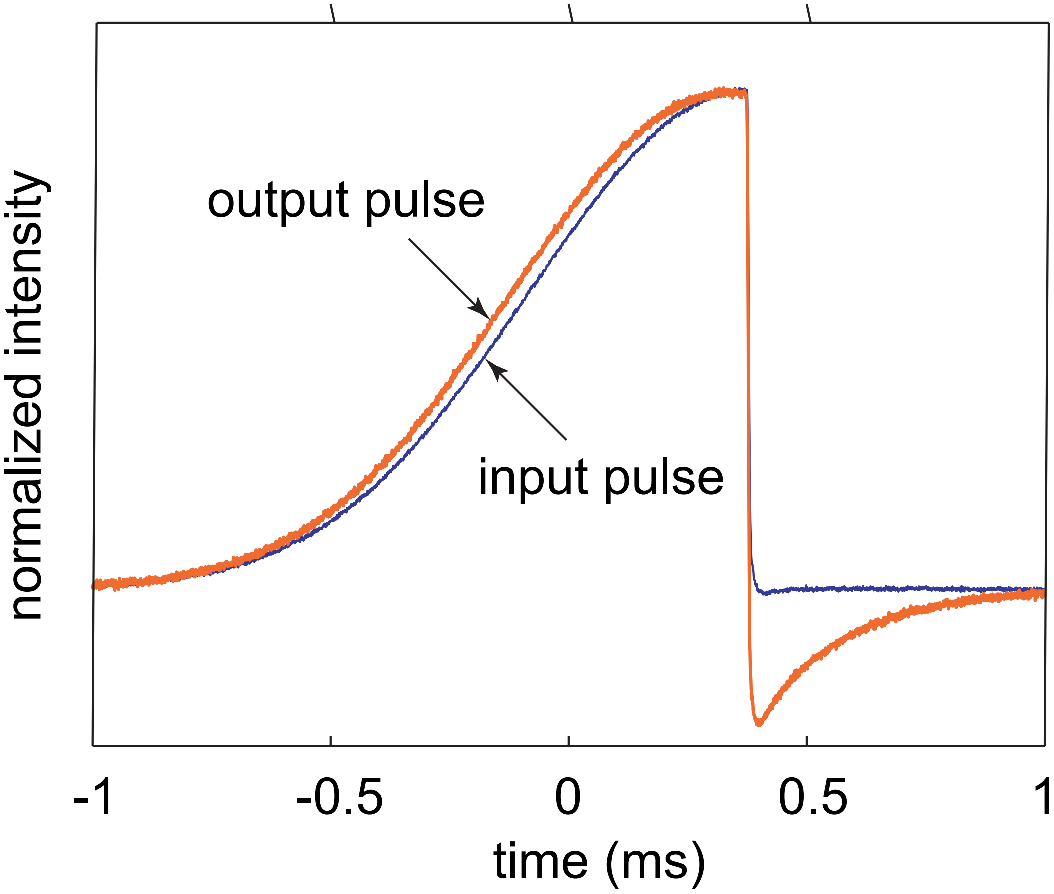


G. Nimtz and A. Haibel, Basics of Superluminal Signals 169

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.

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



Smooth part of pulse propagates at group velocity

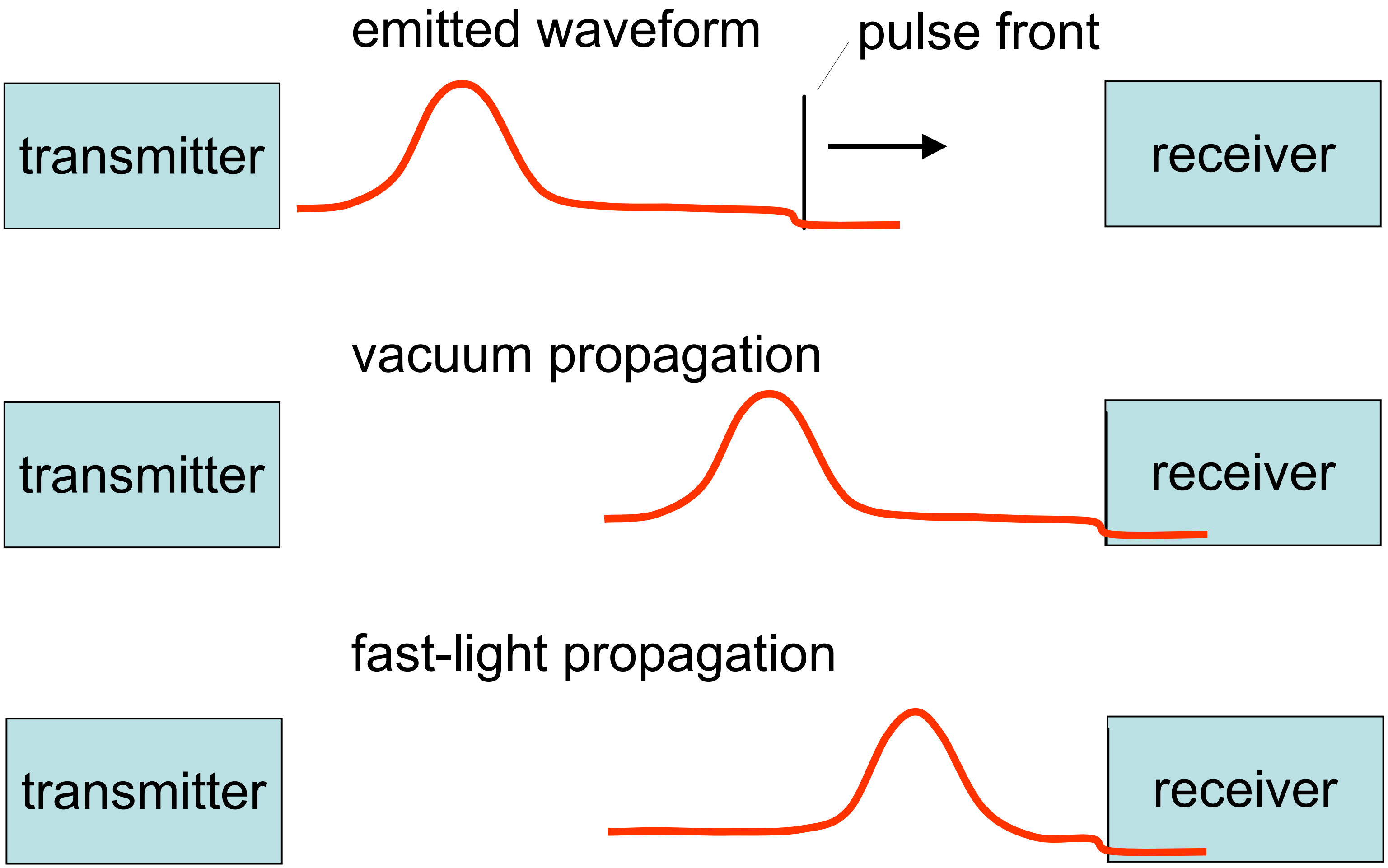
Discontinuity propagates at phase velocity

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



emitted waveform

pulse front

transmitter

receiver

vacuum propagation

transmitter

receiver

fast-light propagation

transmitter

receiver

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

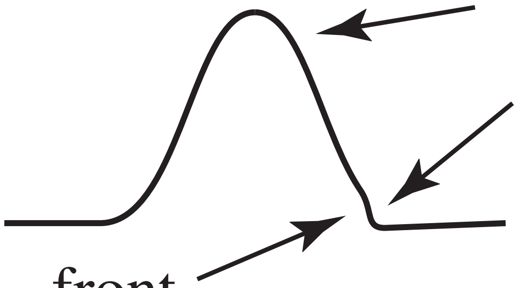
Information Velocity – Tentative Conclusions

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.



which gives better S/N?

front

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?**

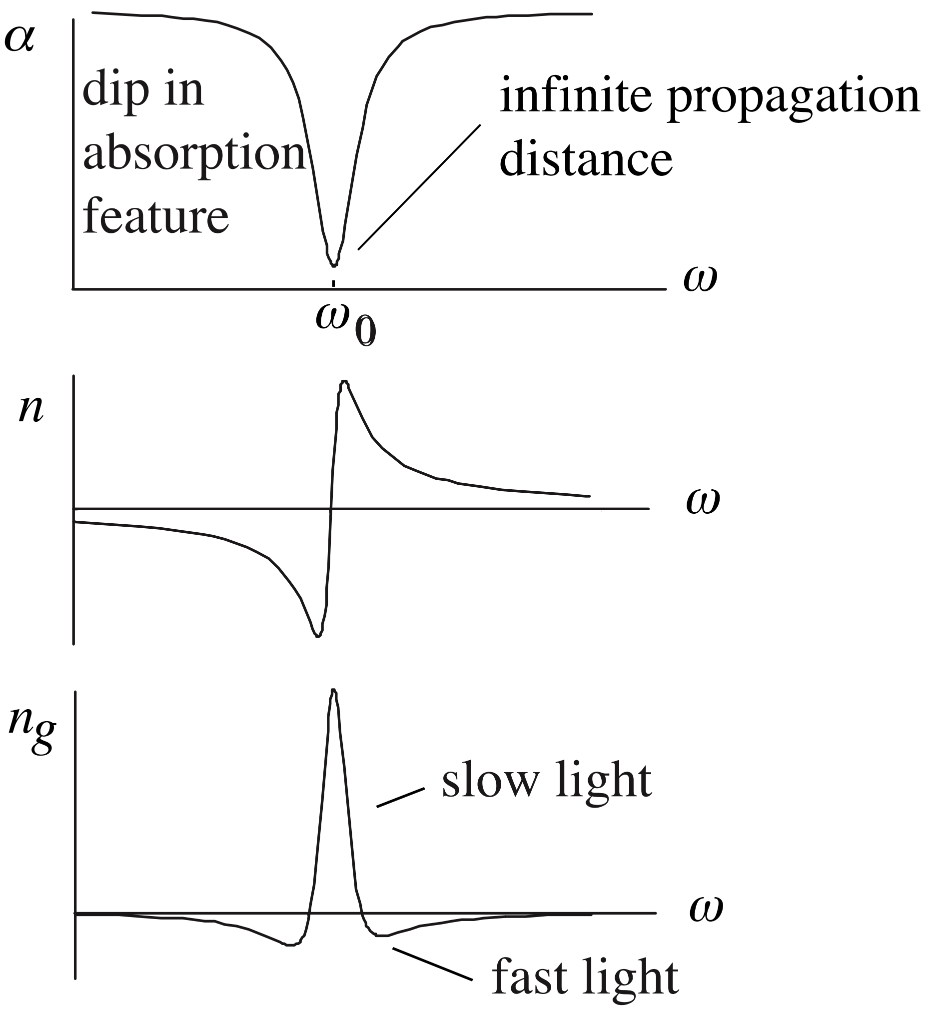
* Boyd, Gauthier, Gaeta, and Willner, PRA 2005

** 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.

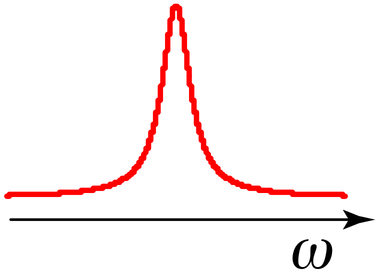
This “trick”works only for slow light.



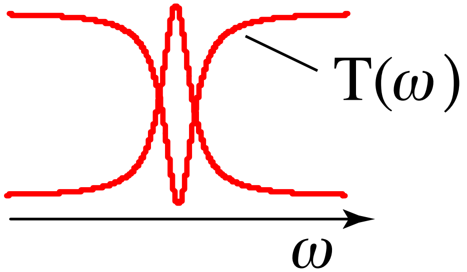
Influence of Spectral Reshaping

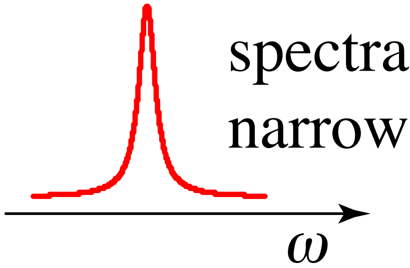
(Line-Center Operation, Dip in Gain or Absorption Feature)

input pulse



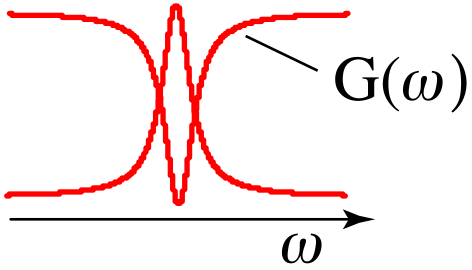
output pulse
slow-light

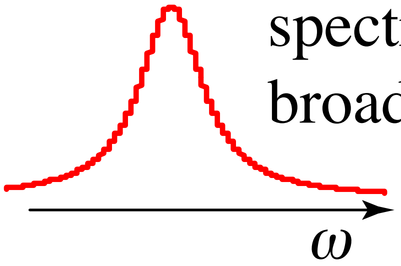




spectrally
narrowed pulse

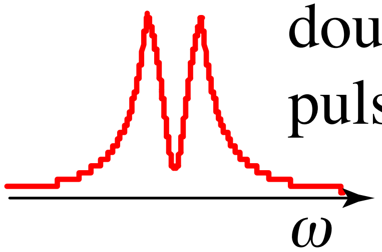
output pulse
fast-light





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.

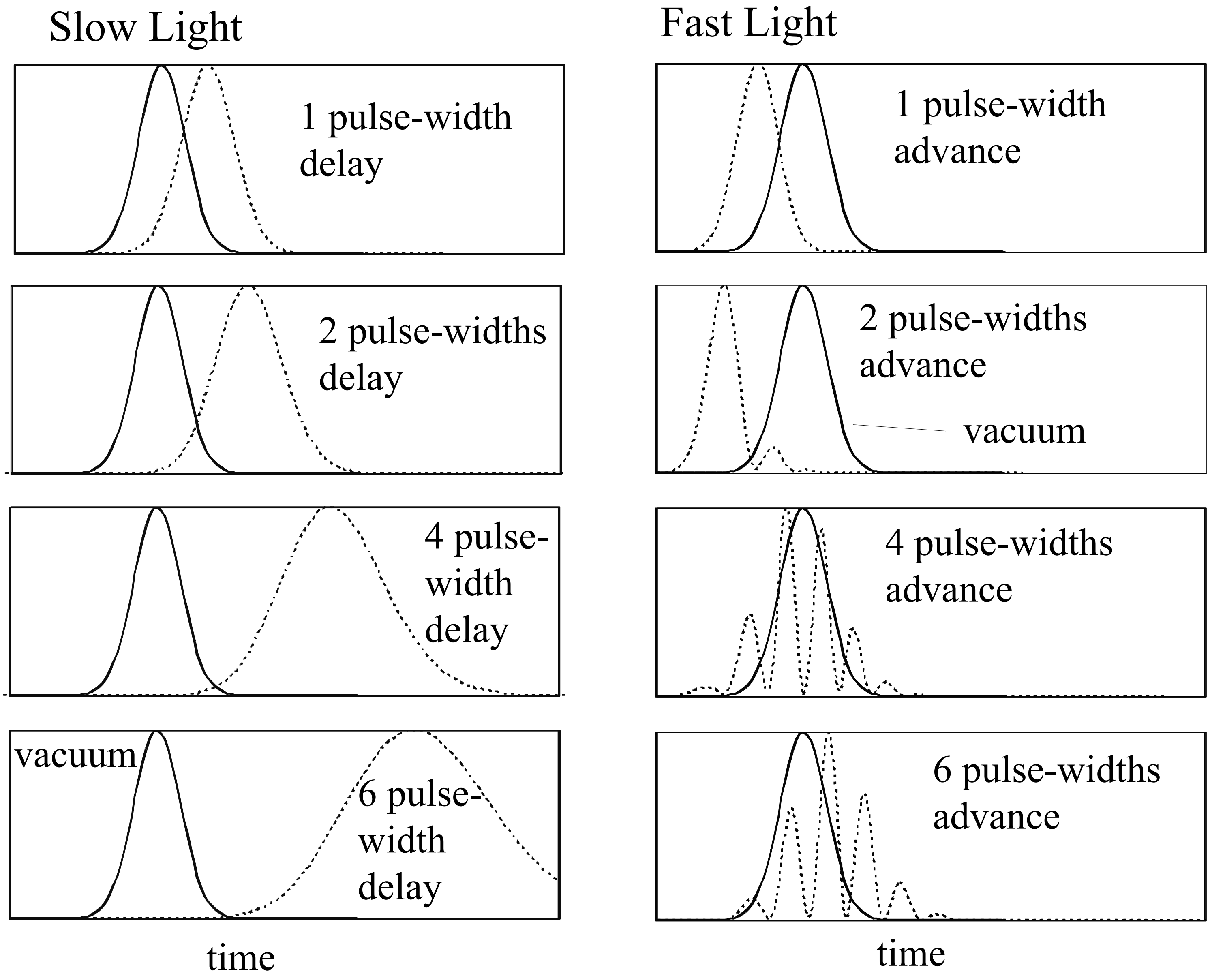
Numerical Results: Propagation through a Linear Dispersive Medium

Full (causal) model – solve wave equation with P = χE where $\chi(\omega) = \dfrac{A}{\omega_0 - \omega - i\Gamma}$

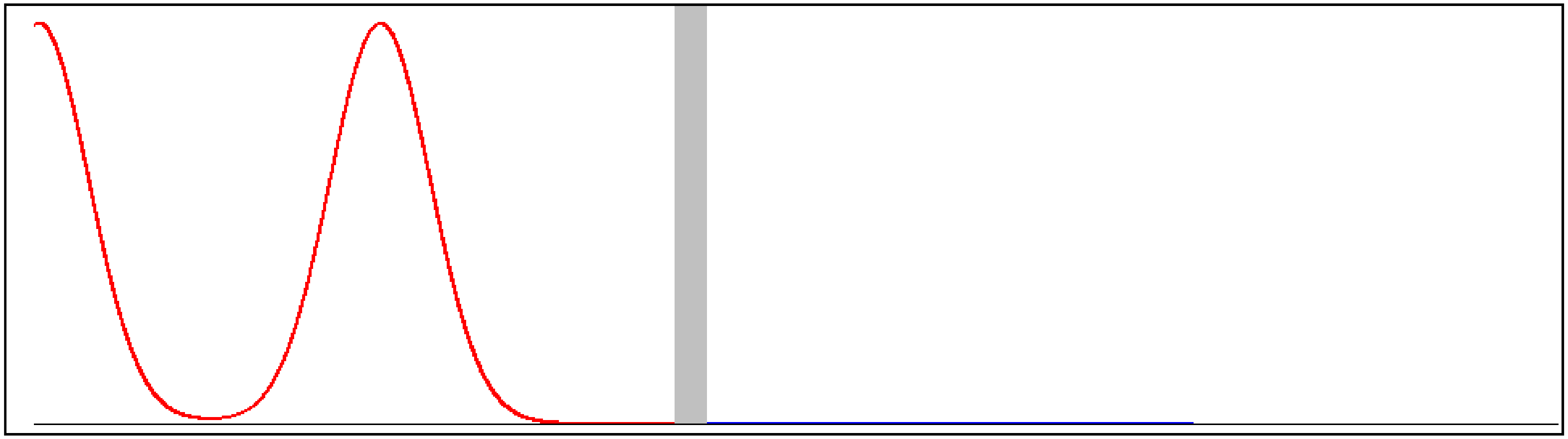
Fast light:
Lorentzian
absorption line
T = exp(-32)
vary line width
to control advance

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

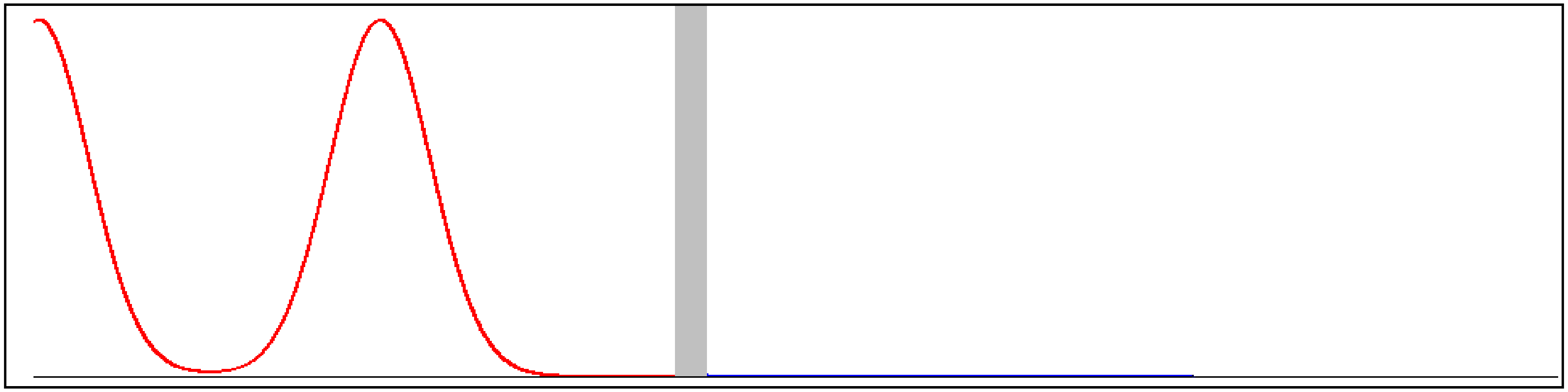
Same Gaussian input
pulse in all cases



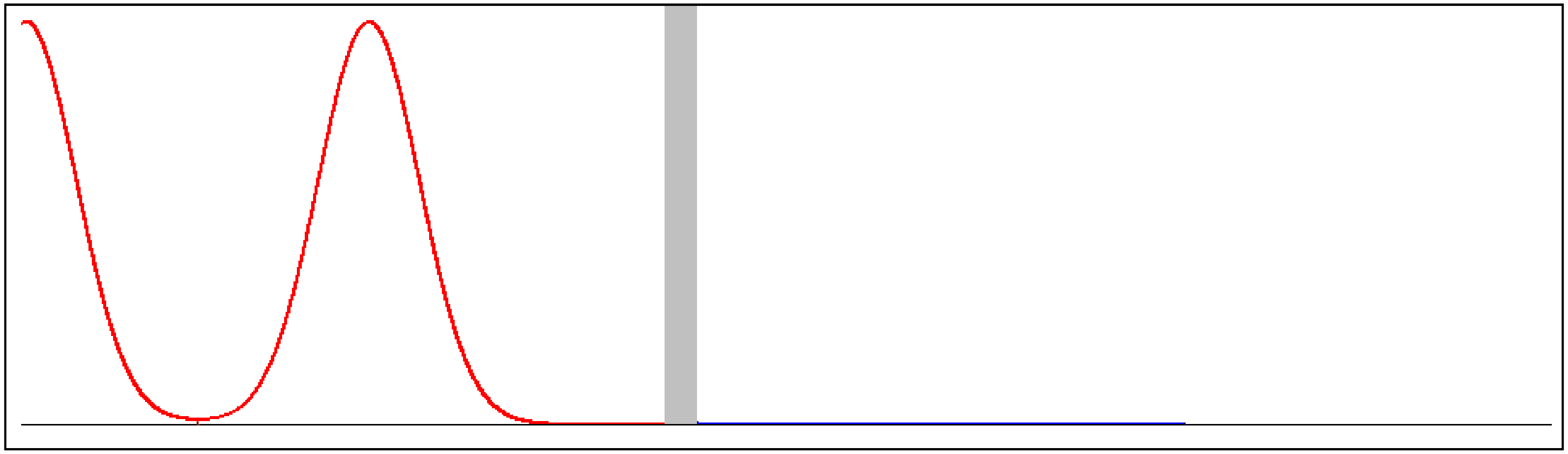
Propagation of Full and Truncated Pulse Trains



Slow

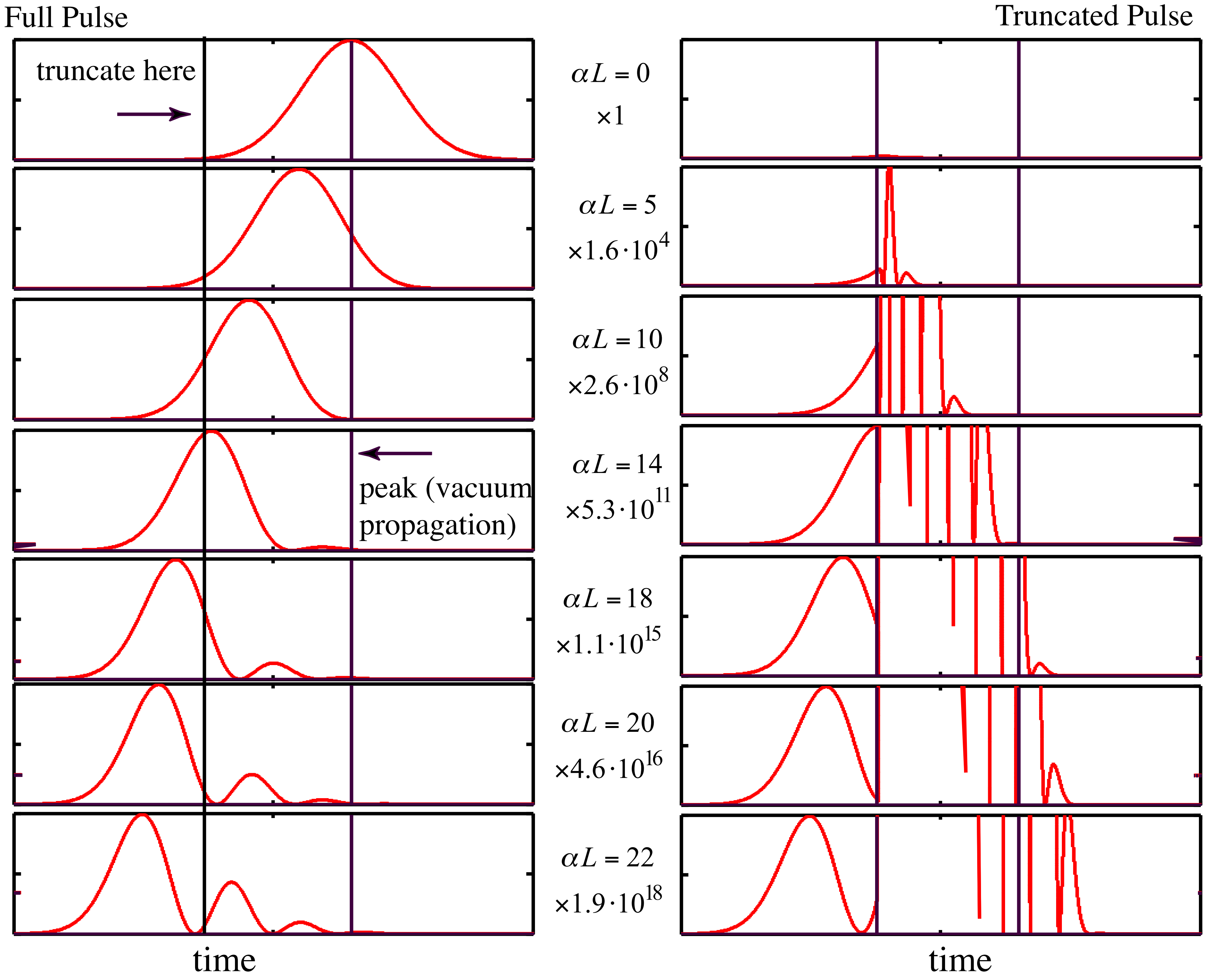


Fast



Fast - truncated

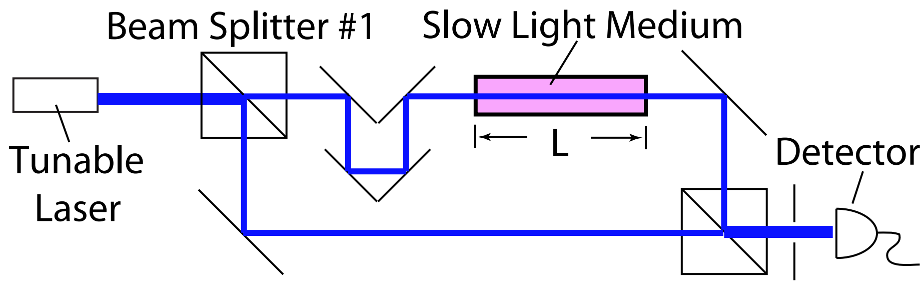
Fast-Light Pulse Propagation: Line-Center Absorbing Medium



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:

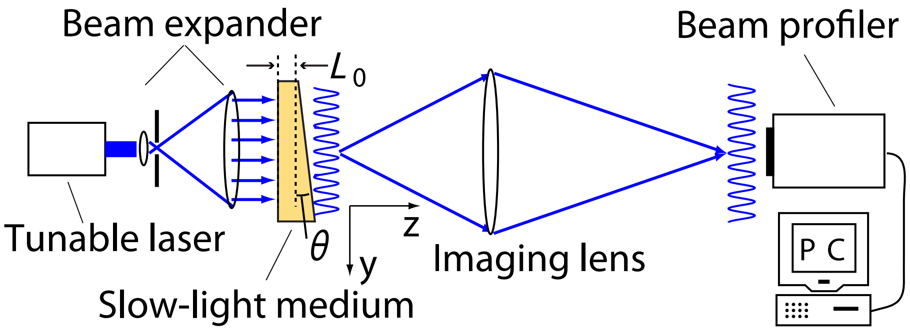


Here is why it works:

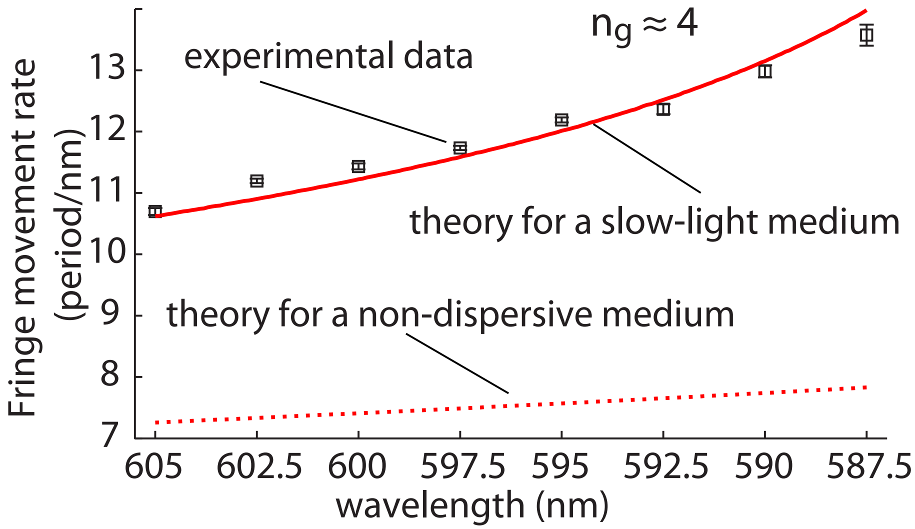
$$\frac{d\Delta\phi}{d\omega} = \frac{d}{d\omega}\left(\frac{\omega n L}{c}\right) = \frac{L}{c}\left(n + \omega\frac{dn}{d\omega}\right) = \frac{L n_g}{c}$$

Shih et al, Opt. Lett. 2007

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

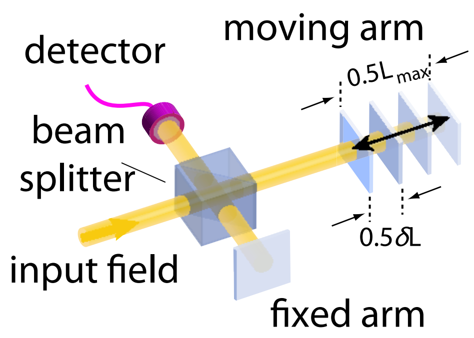


Our experimental results

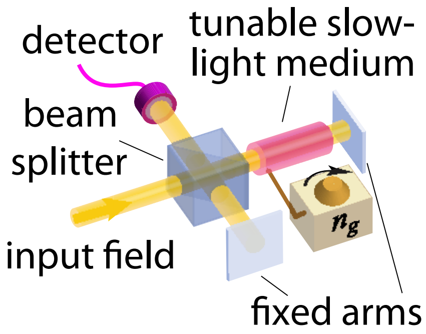


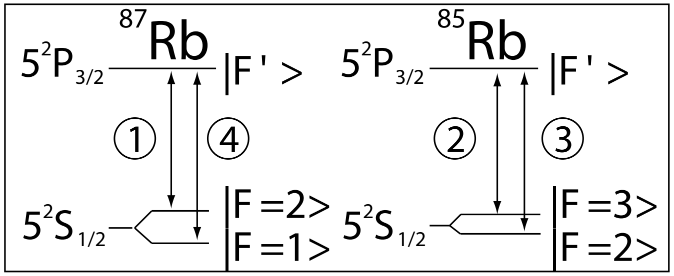
High-Resolution Slow-Light Fourier Transform Interferometer

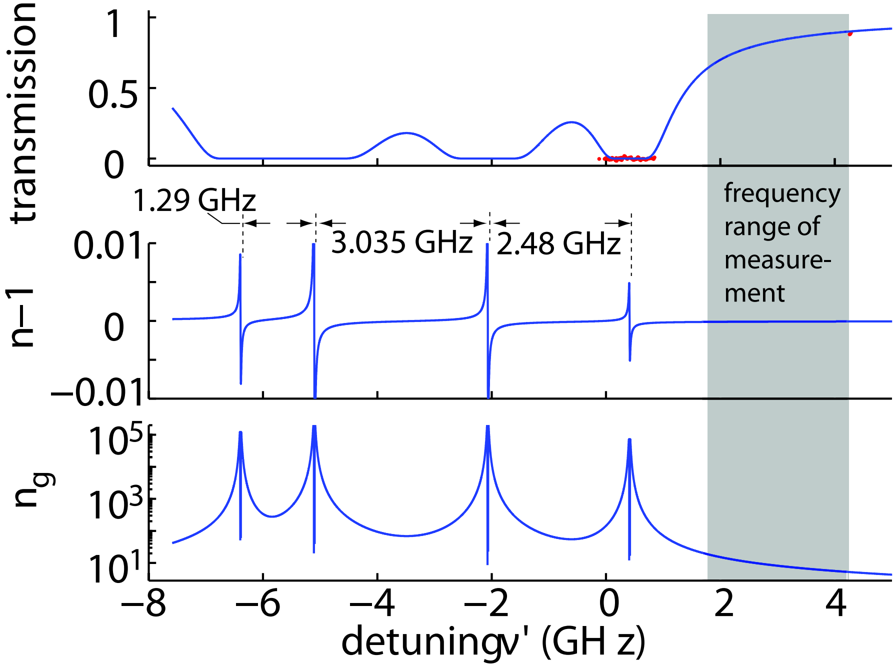
conventional FT Interferometer

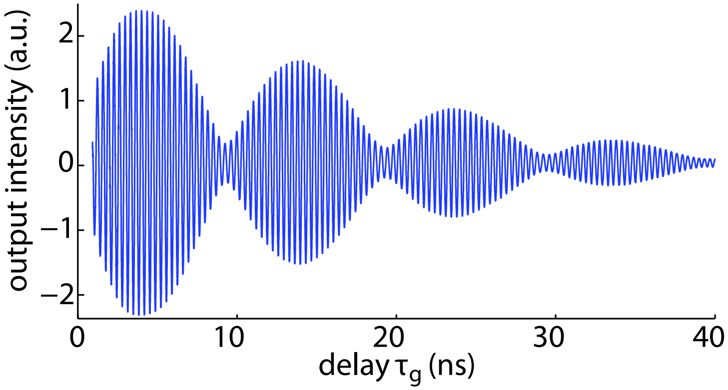


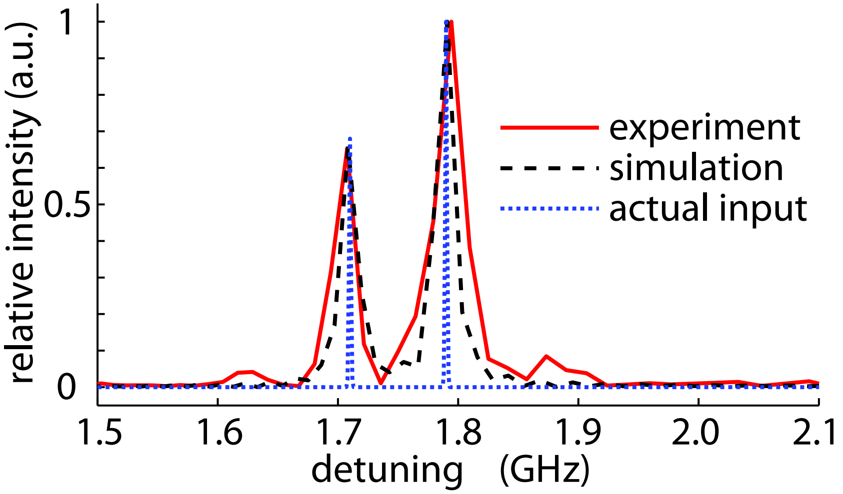
slow-light FT Interferometer





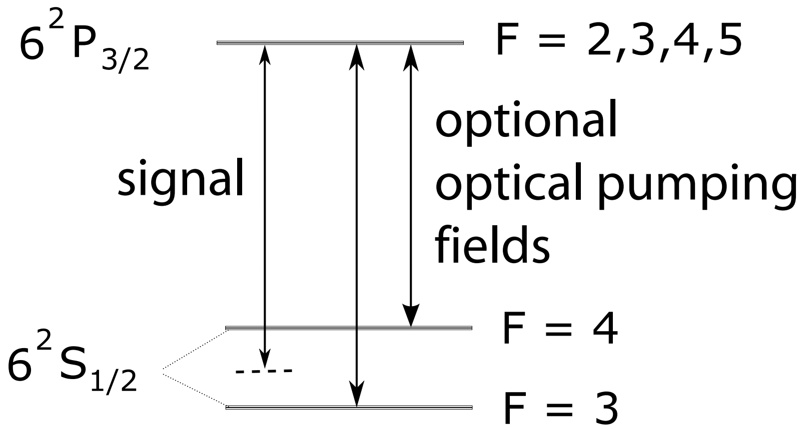






Shi, Boyd, Camacho, Setu, and Howell

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



$6^2P_{3/2}$ F = 2,3,4,5

signal

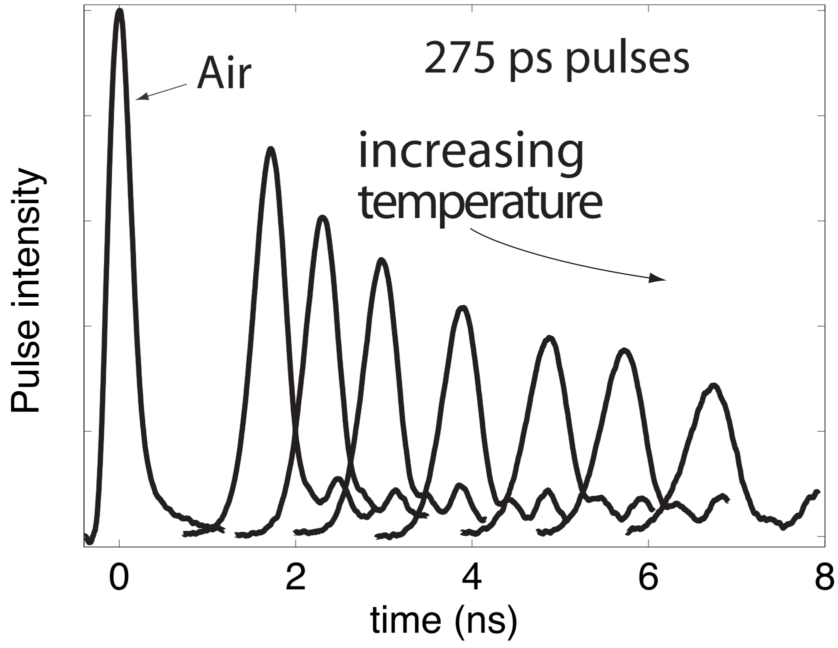
optional optical pumping fields

$6^2S_{1/2}$ F = 4

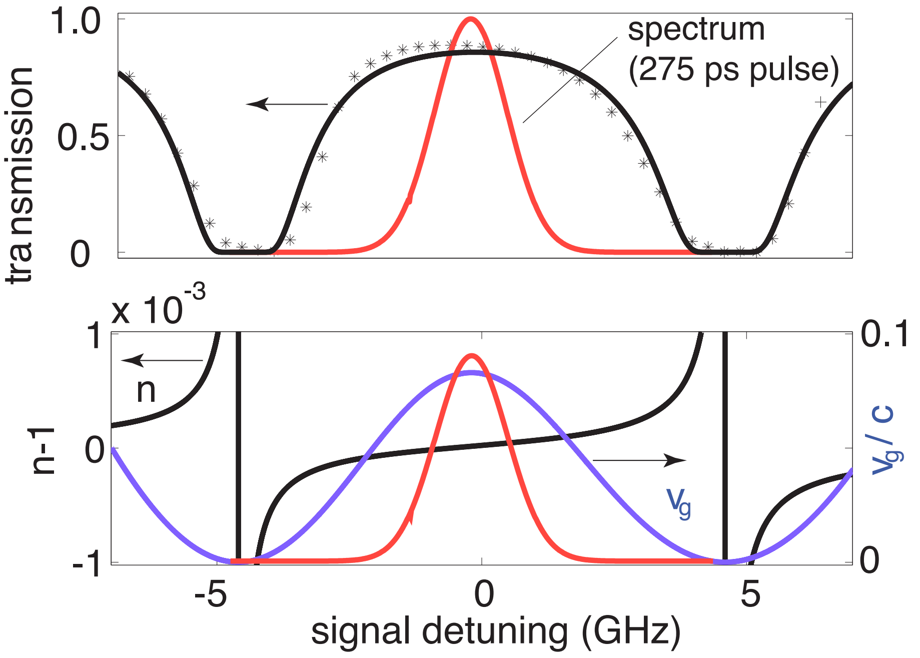
F = 3

group index approximately 10 to 100

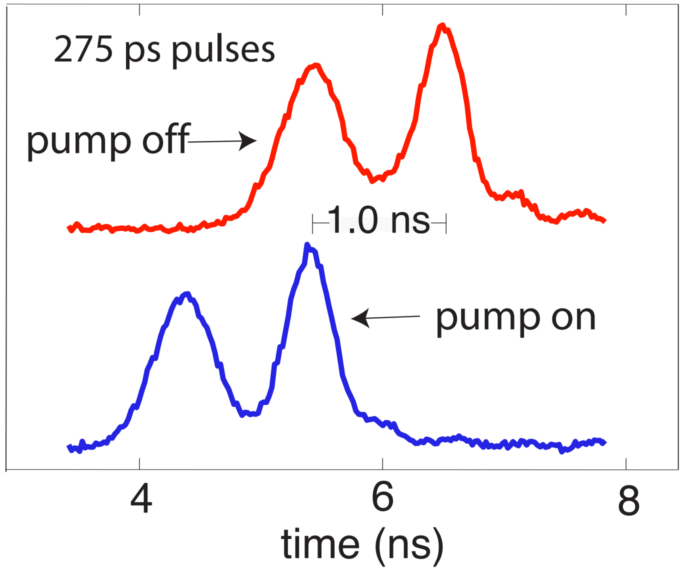
- coarse tuning: temperature



Camacho, Peck, Howell, Schweinsberg, Boyd

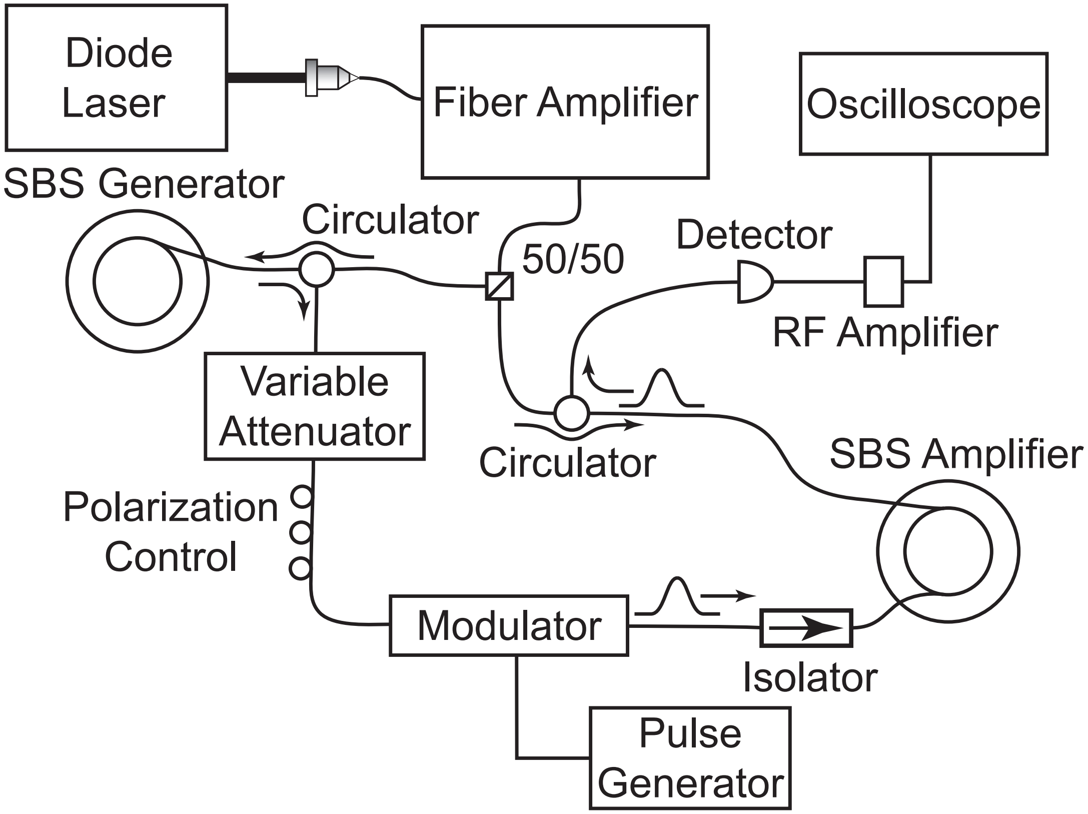


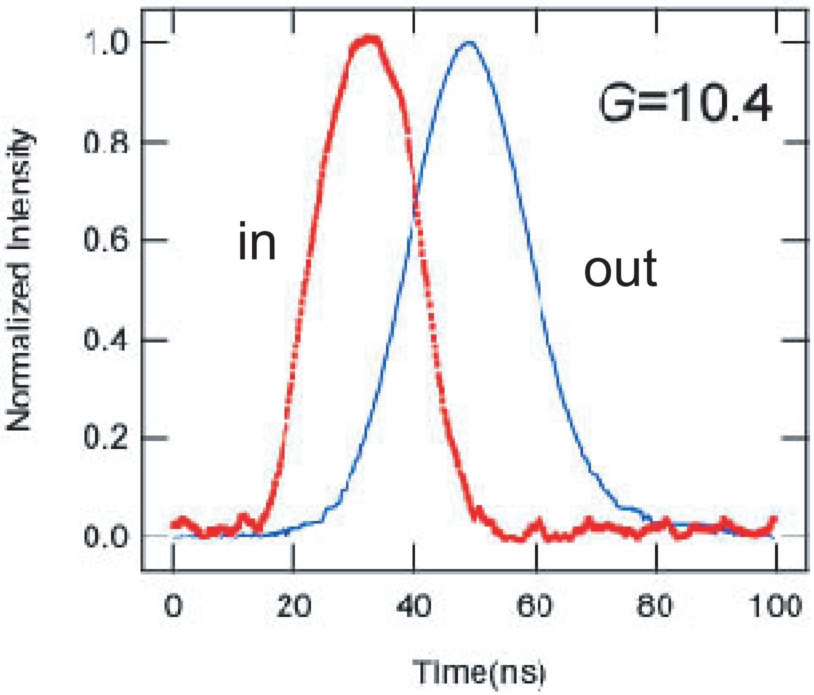
- fine tuning: optical pumping



Slow-Light via Stimulated Brillouin Scattering

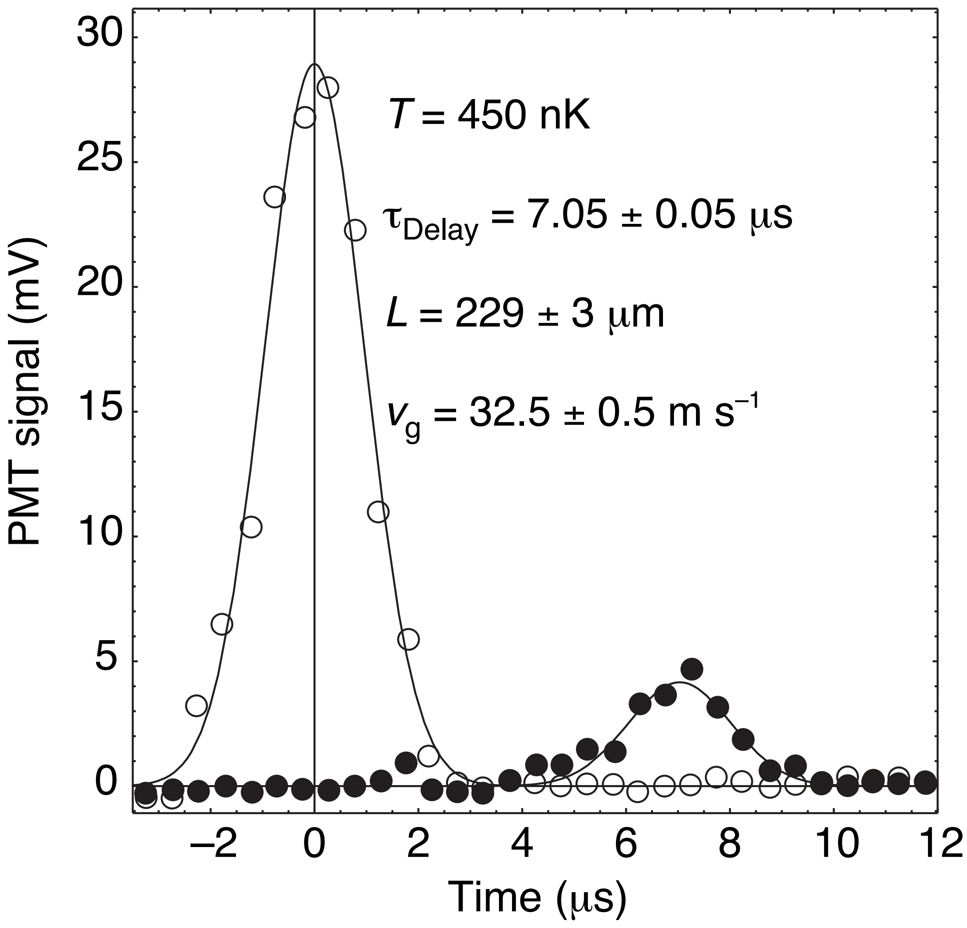
- Rapid spectral variation of the refractive response associated with SBS gain leads to slow light propagation
- Supports bandwidth of 100 MHz, large group delays
- Even faster modulation for SRS



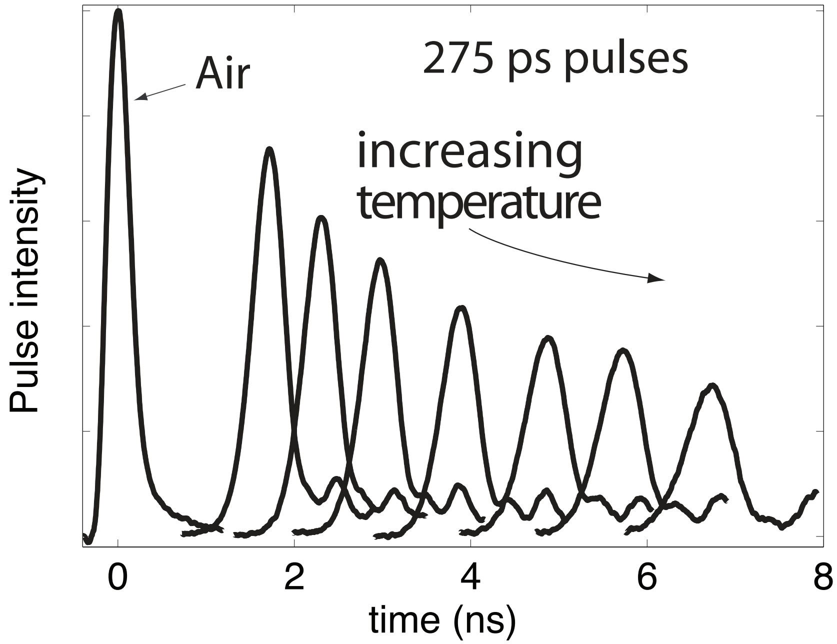

typical data

Okawachi, Bigelow, Sharping, Zhu, Schweinsberg, Gauthier, Boyd, and Gaeta Phys. Rev. Lett. 94, 153902 (2005).
Related results reported by Song, González Herráez and Thévenaz, Optics Express 13, 83 (2005).

Summary – Progress in Slow-Light Research

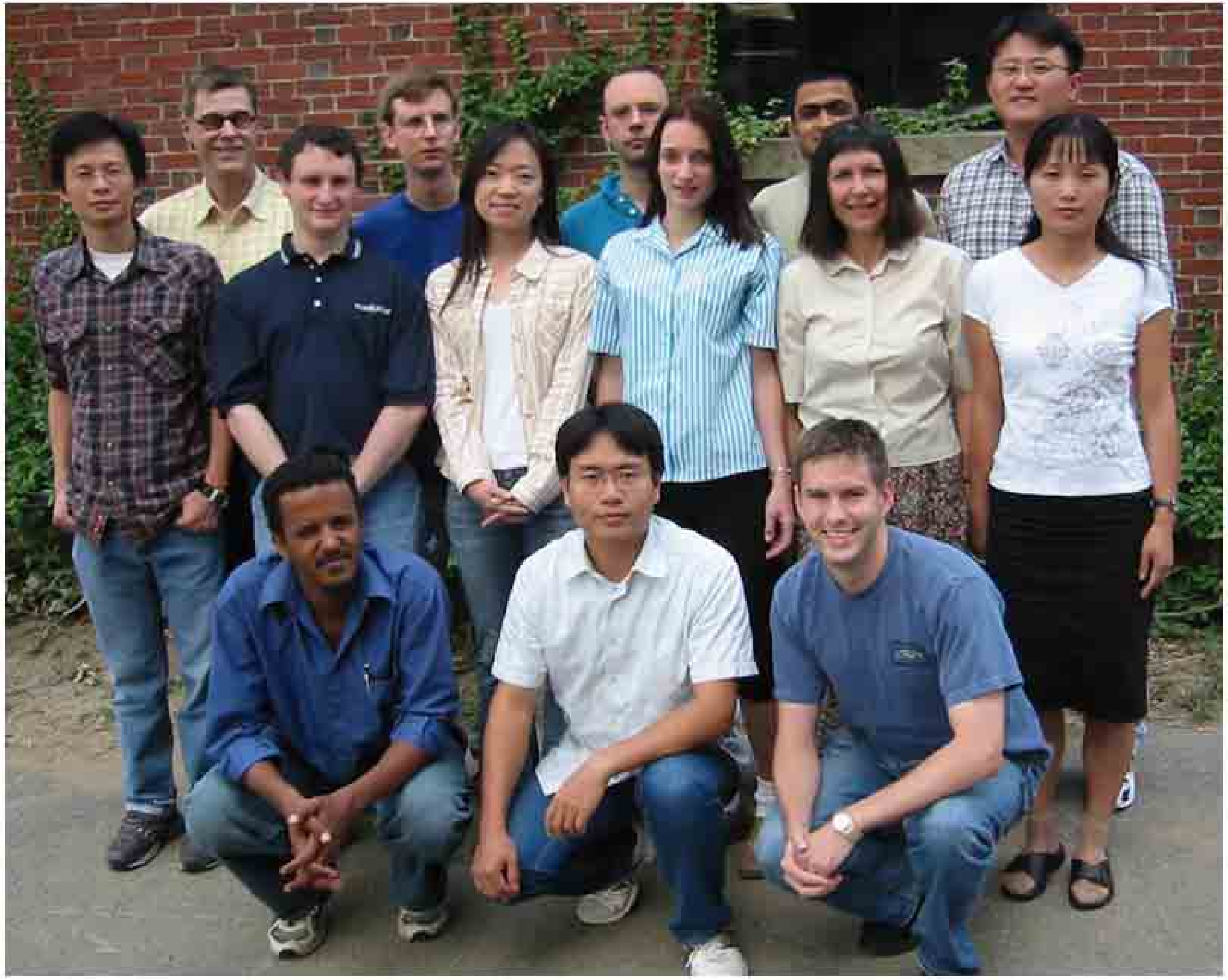


Delay of 3 pulse widths (1999)
Results of Hau, L



Delay of 80 pulse widths (2007)
Results of Howell

Special Thanks to My Students and Research Associates



Thank you for your attention!

And thanks to NSF and DARPA for financial support!

Our results are posted on the web at:

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

Physics is all about asking the right questions

Just ask

- Evelyn **Hu**
- **Watt** Webb (or James **Watt**)
- Michael **Ware**
- **Wen** I Wang
- Kam **Wai** Chan

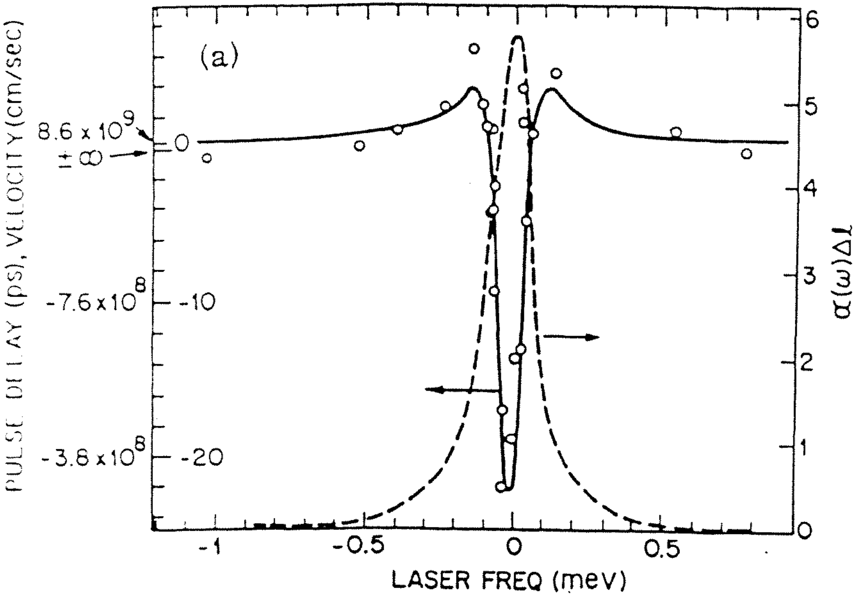
Not to mention

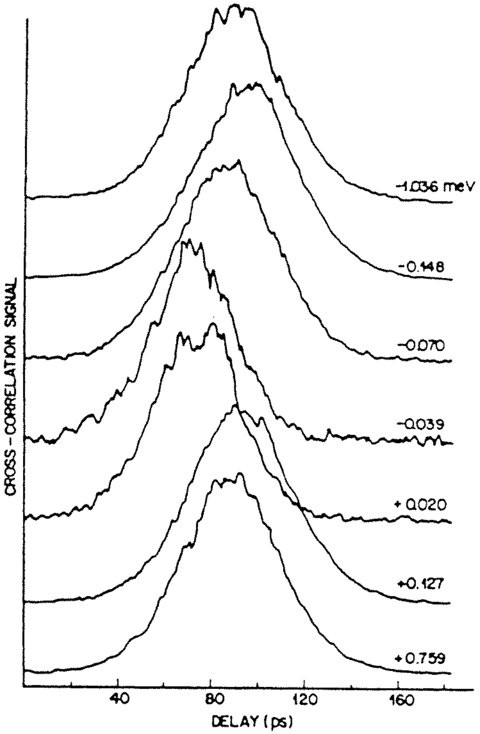
- Lene **Hau**

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).

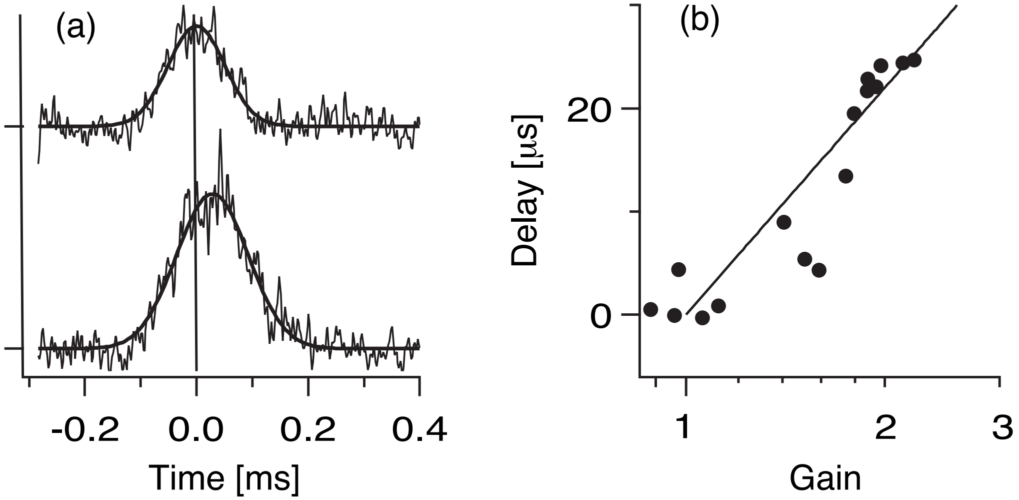
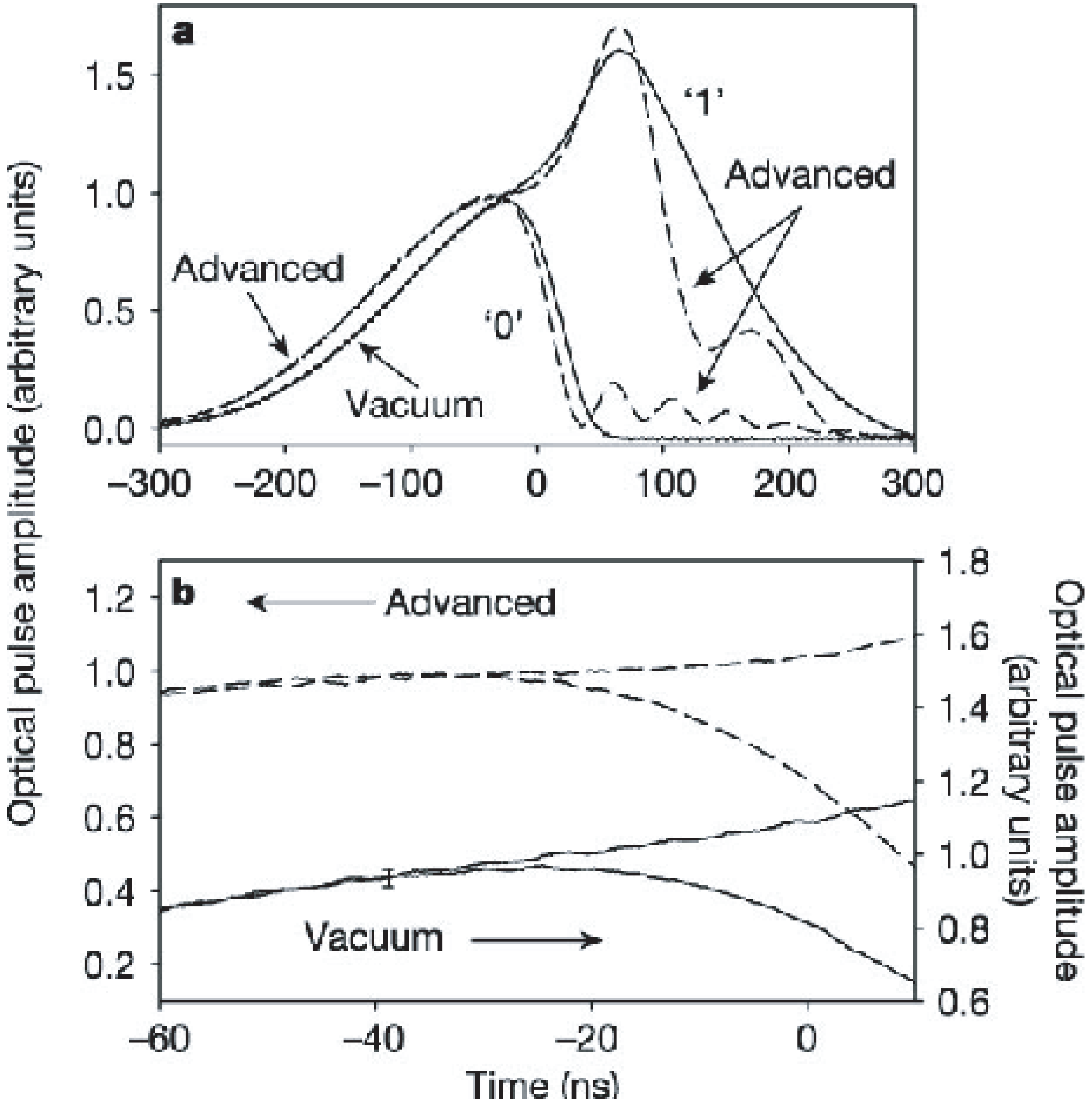


FIG. 3. Pulse delay due to light amplification. (a) About 20 ms delay was observed when a Gaussian pulse of about 140 ms width and 0.11 mW/cm^2 peak intensity was sent through the dressed condensate (bottom trace). The top trace is a reference taken without the dressed condensate. Solid curves are Gaussian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

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."

$v_i \leq c$