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

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

Presented at AITA 9, Advanced Infrared Technology and Applications, Leon, Mexico, October 8-12, 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

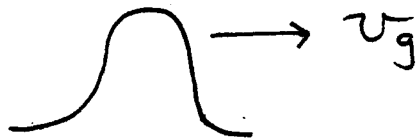
Implications for quantum information

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

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

Group Velocity

Pulse
(wave packet)



Group velocity given by $v_g = \dfrac{d\omega}{dk}$

For $k = \dfrac{n\omega}{c}$. $\dfrac{dk}{d\omega} = \dfrac{1}{c}\left(n + \omega \dfrac{dn}{d\omega}\right)$

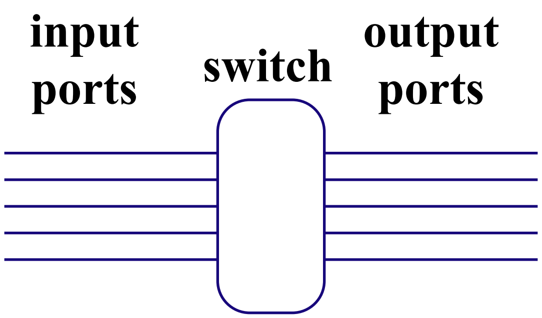
Thus

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

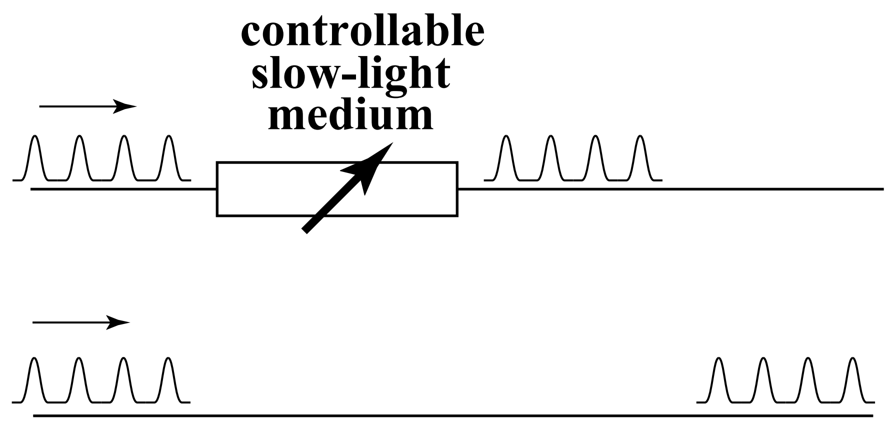
Thus $n_g \neq n$ in a dispersive medium!

Slow Light and Optical Buffers

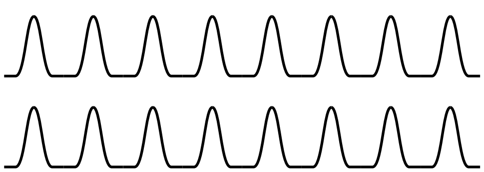
All-Optical Switch



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

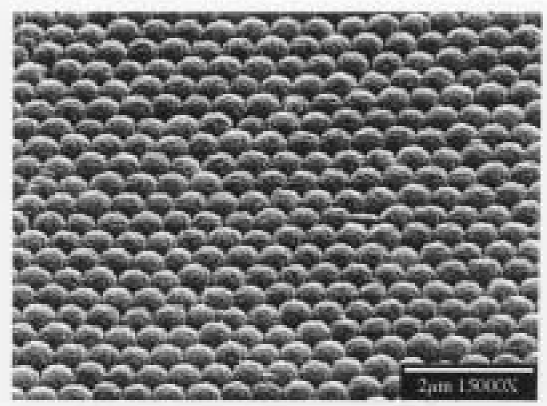
- Use the linear response of atomic systems

  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

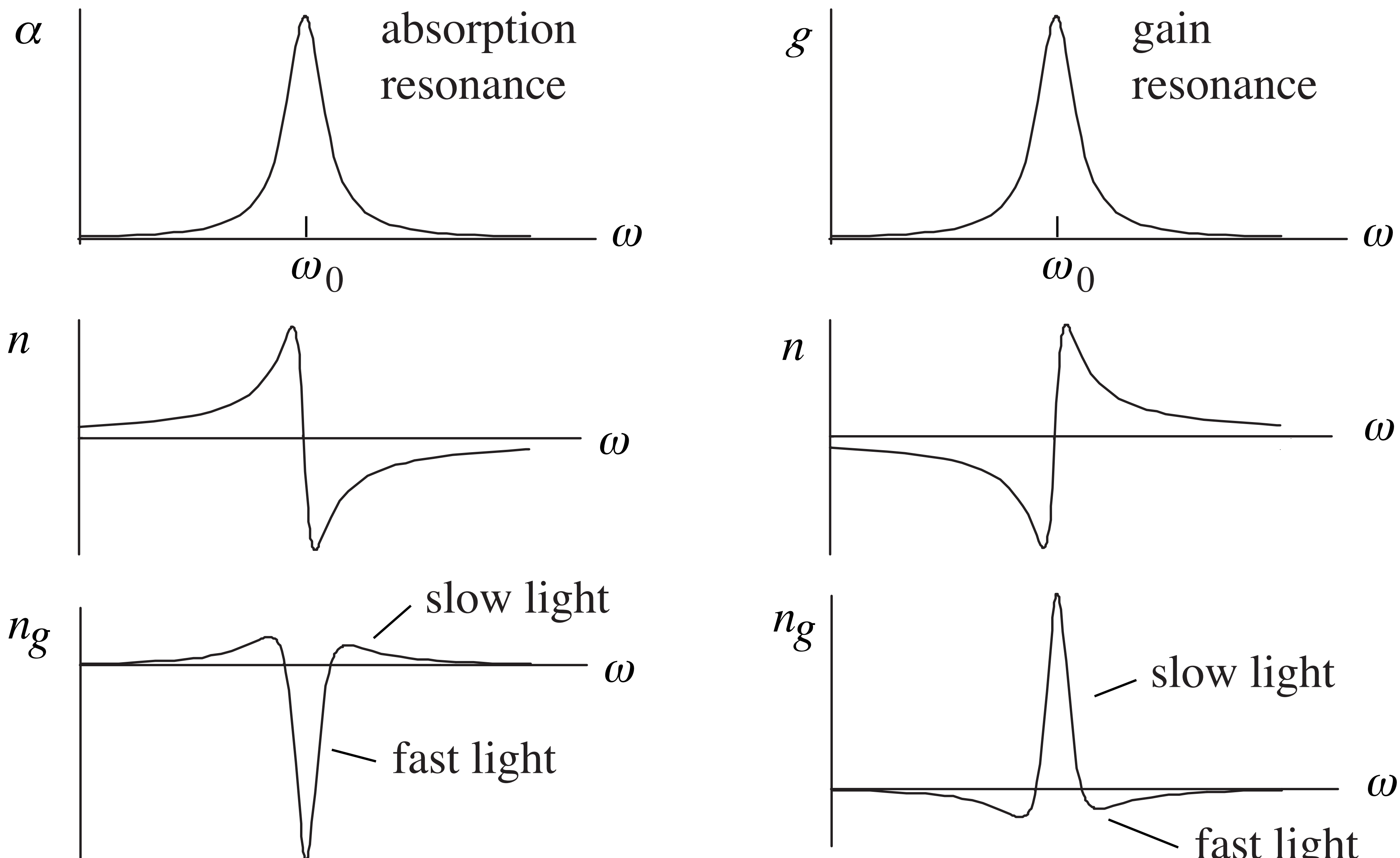
$$v_g = \frac{c}{n_g} \qquad\qquad n_g = n + \omega \frac{dn}{d\omega}$$

Want large dispersion to obtain extreme group velocities

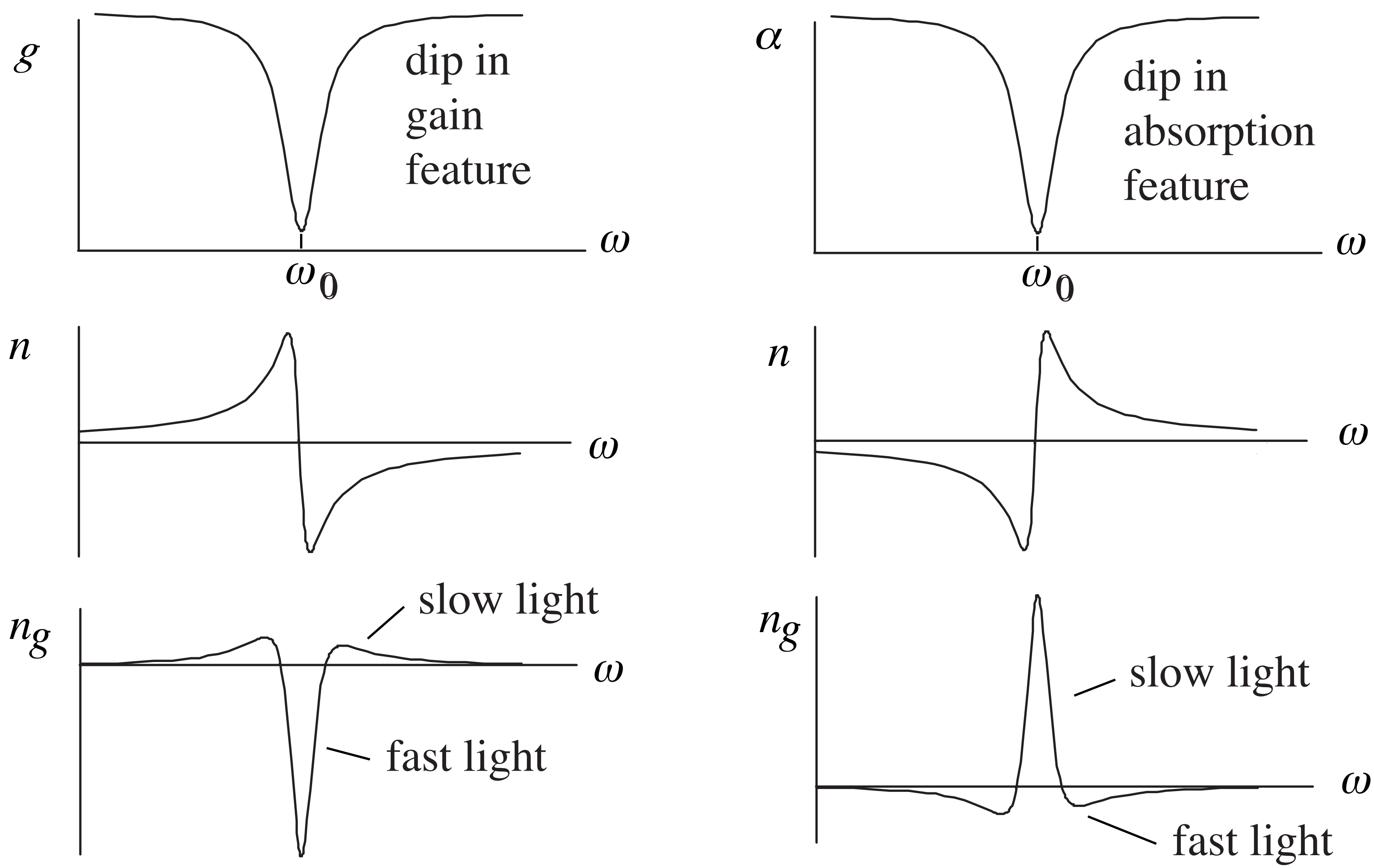
Sharp spectral features produce large dispersion.

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

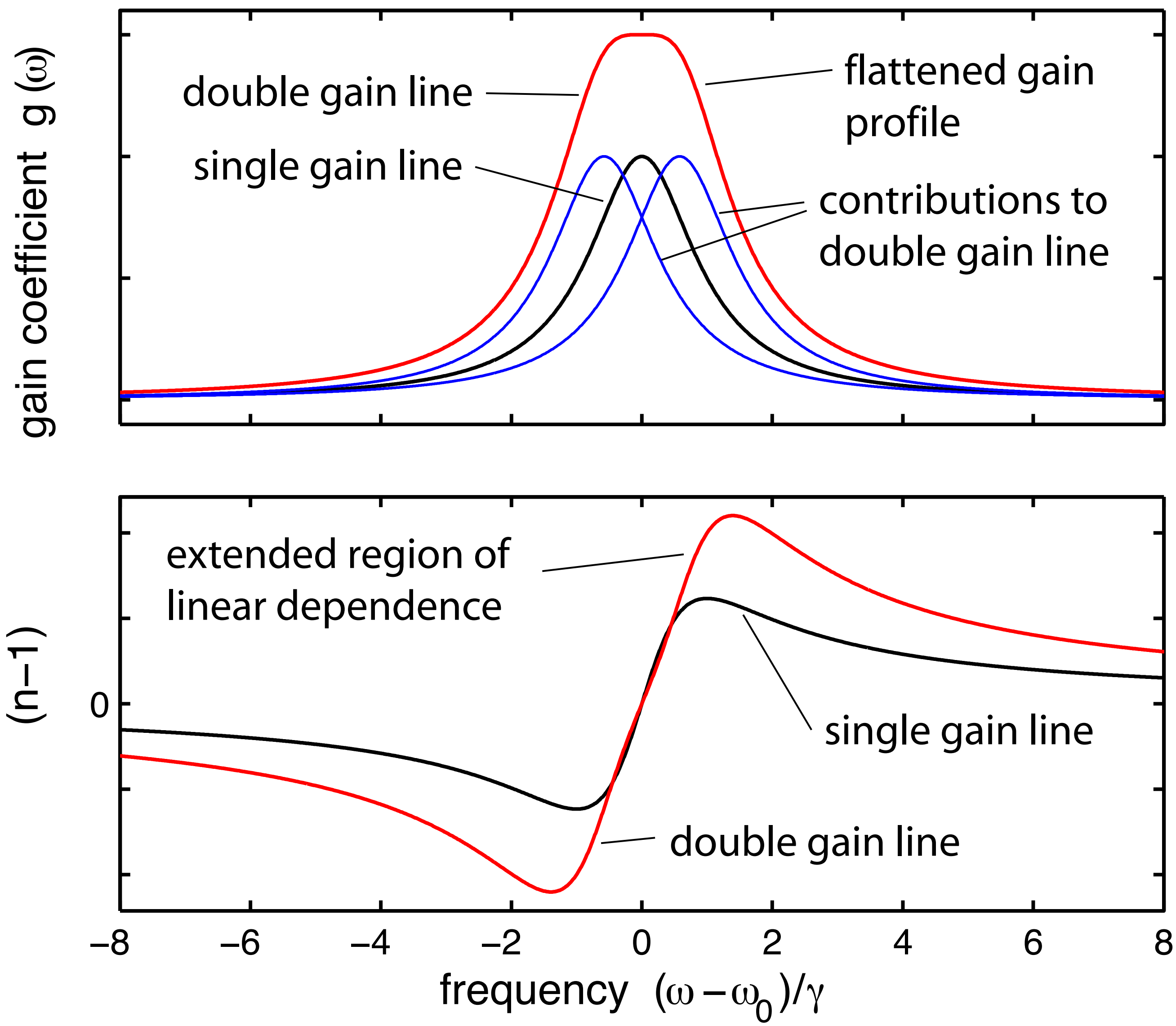


How to Create Slow and Fast Light II – Use Dip in Gain or Absorption Feature



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

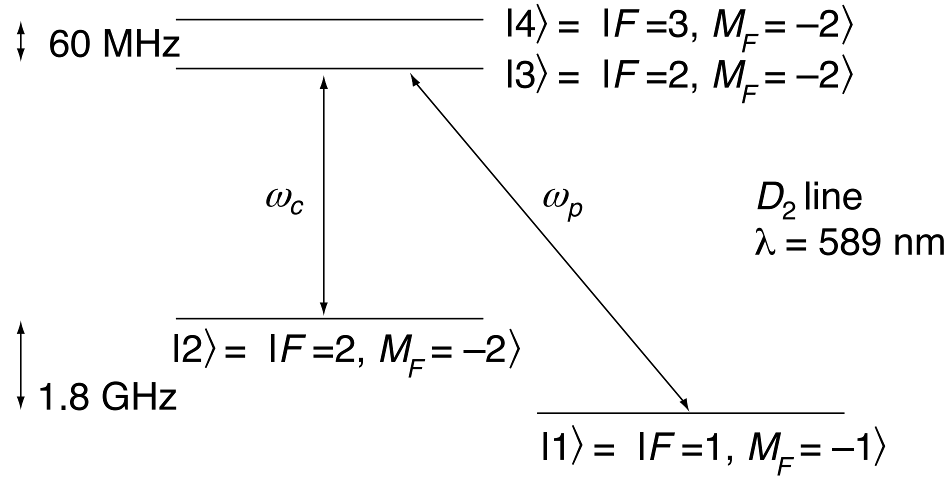
* from F. Bitter and H. Medicus, Fields and particles; an introduction to electromagnetic wave phenomena and quantum physics

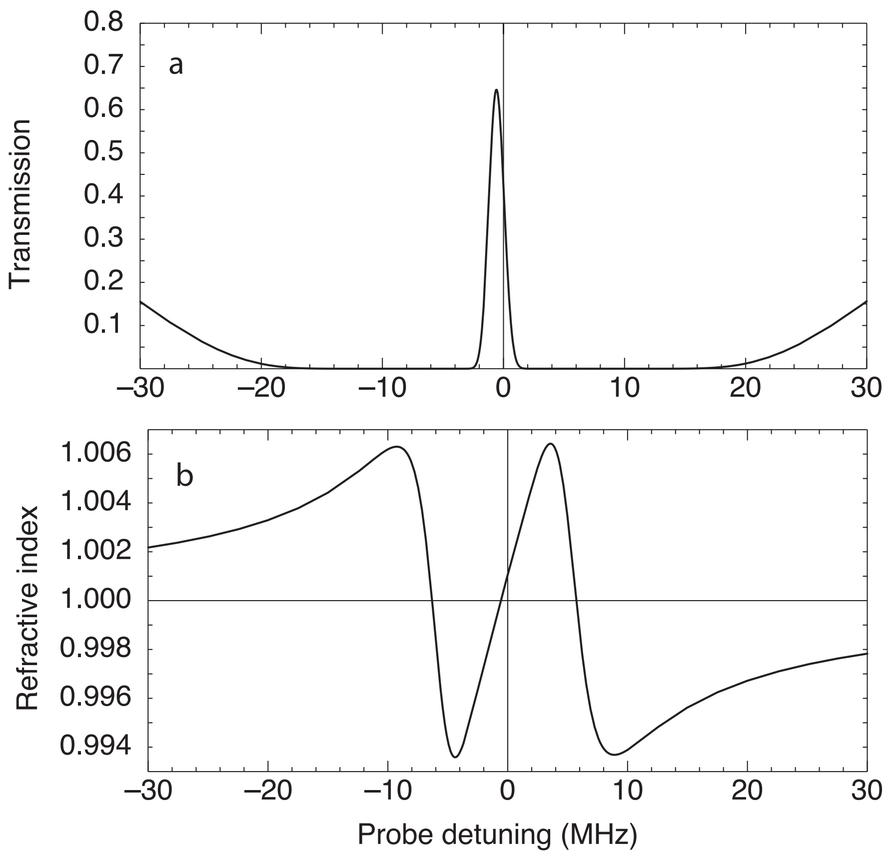
Light speed reduction to 17 metres per second in an ultracold atomic gas

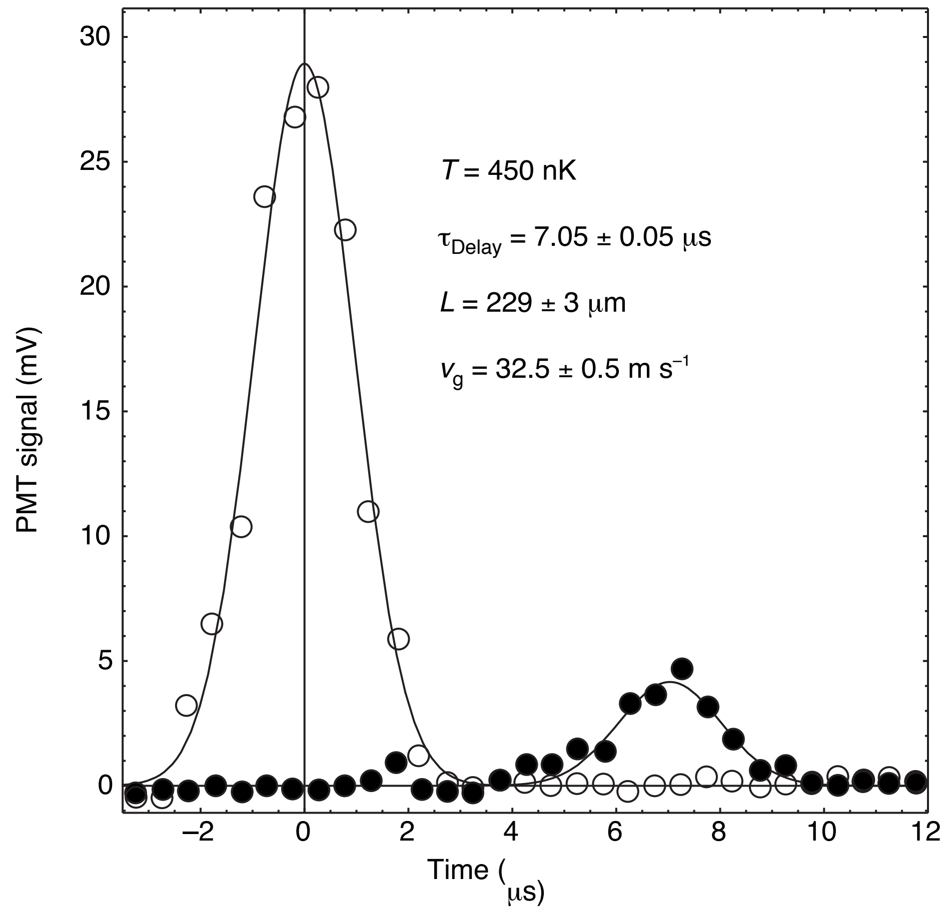
Lene Vestergaard Hau*[2], S. E. Harris[3], Zachary Dutton*[2] & Cyrus H. Behroozi*§

* 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



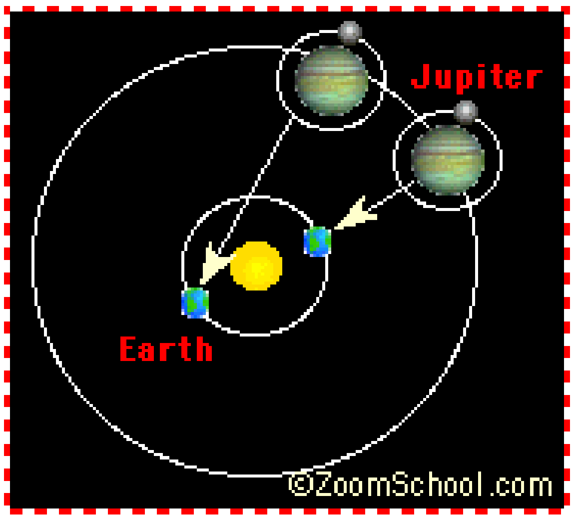




Determination of the Velocity of Light*
"Astronomical" Methods

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

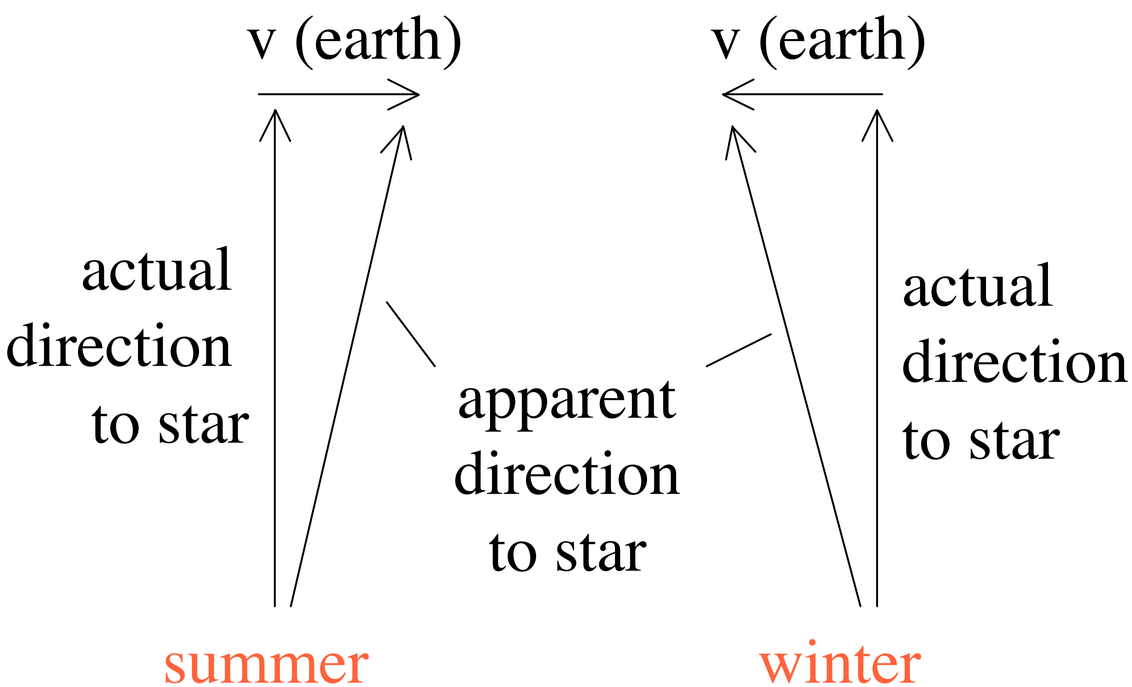
(Actually, light transit time from sun to earth is just over 8 minutes, and c = 299,793 km/sec)

*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.



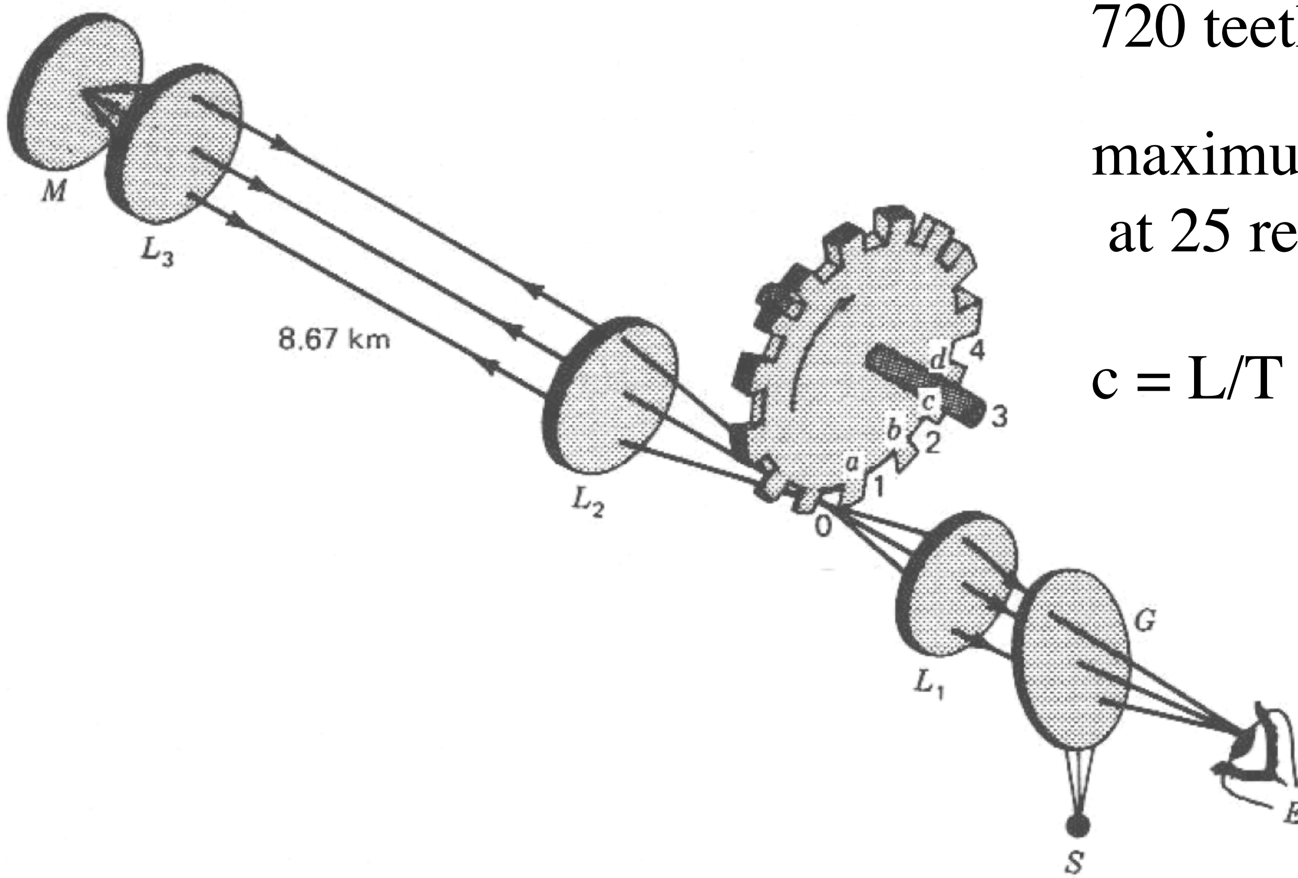
$$v(\text{earth}) \approx 30 \text{ km/s}$$

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

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

Determination of the Velocity of Light
Laboratory Methods

Fizeau (1849) Time-of-flight method



720 teeth in wheel

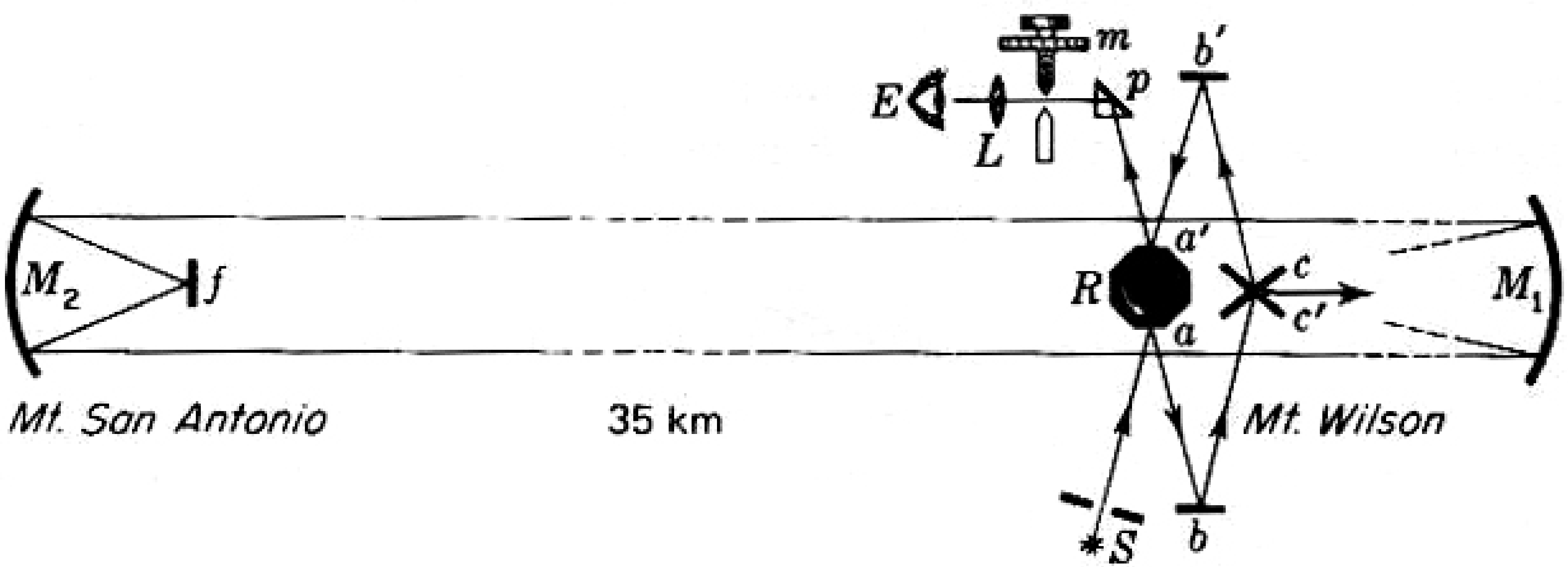
maximum transmission at 25 revolutions/sec

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

Determination of the Velocity of Light

Laboratory Methods

Michelson (1926); Improved time of flight method.



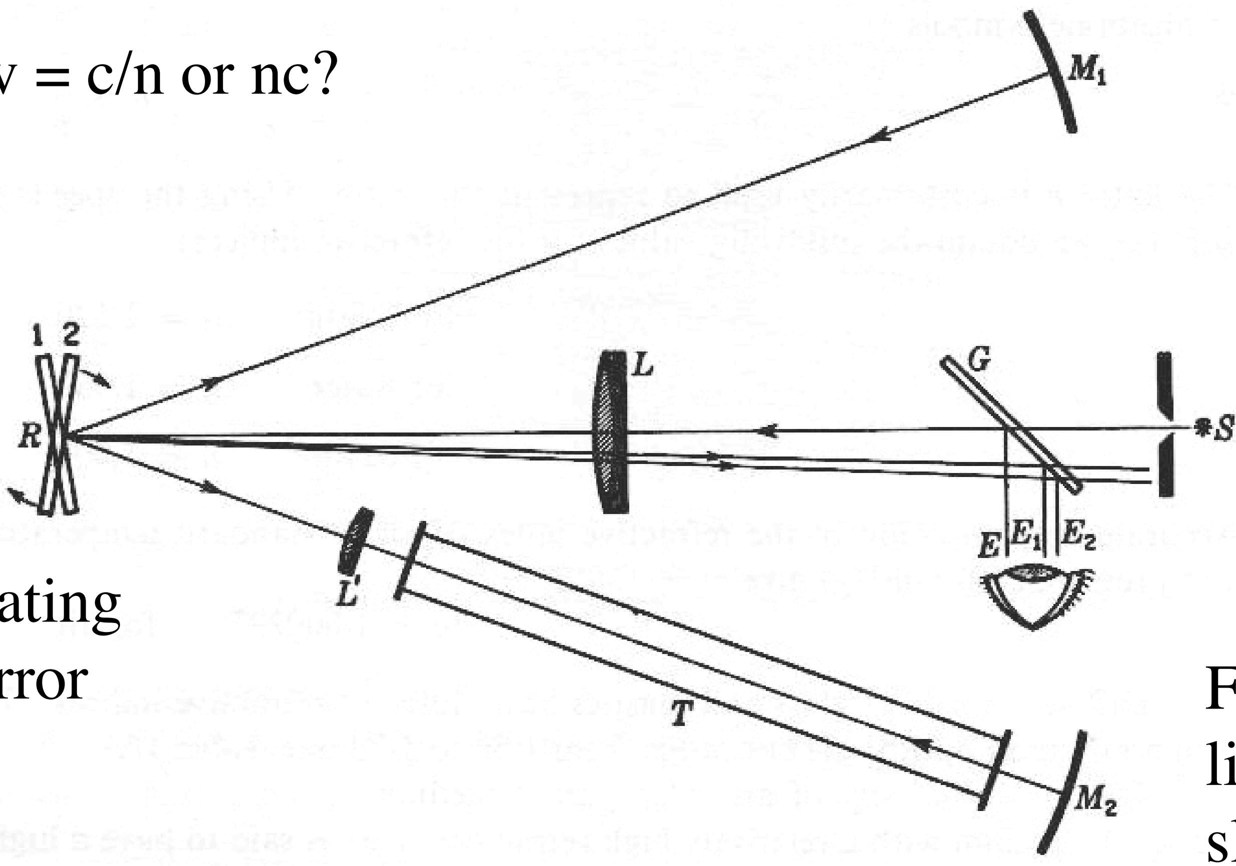
Rotating octagonal mirror

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?



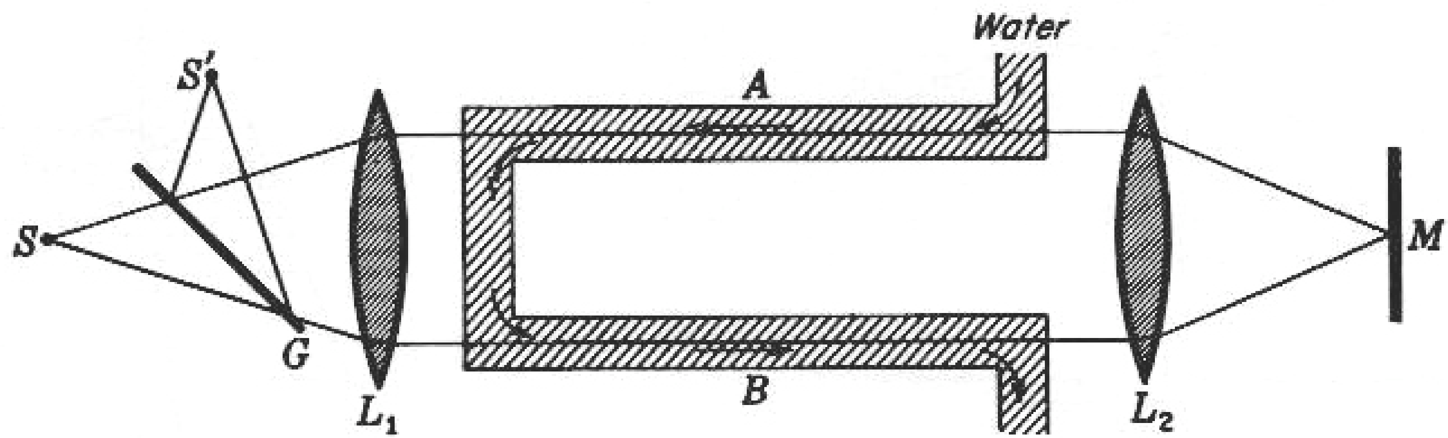
rotating
mirror

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

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

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)

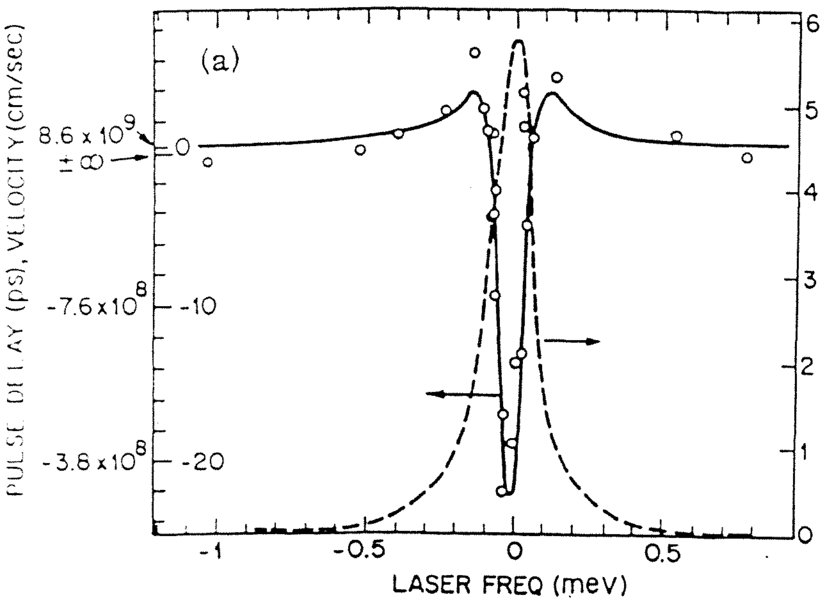
The frequency and wavelength of the methane-stabilized laser at 3.39 μm were directly measured against the respective primary standards. With infrared frequency synthesis techniques, we obtain $\nu = 88.376\,181\,627(50)$ THz. With frequency-controlled interferometry, we find $\lambda = 3.392\,231\,376(12)$ 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.

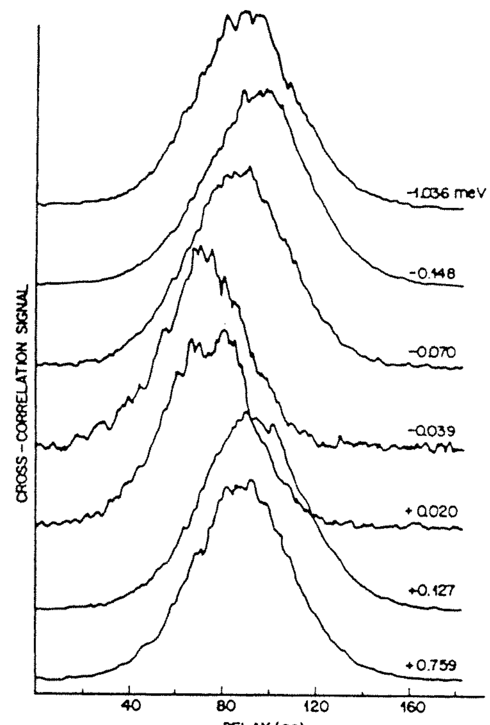
c = 299 792 458

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).

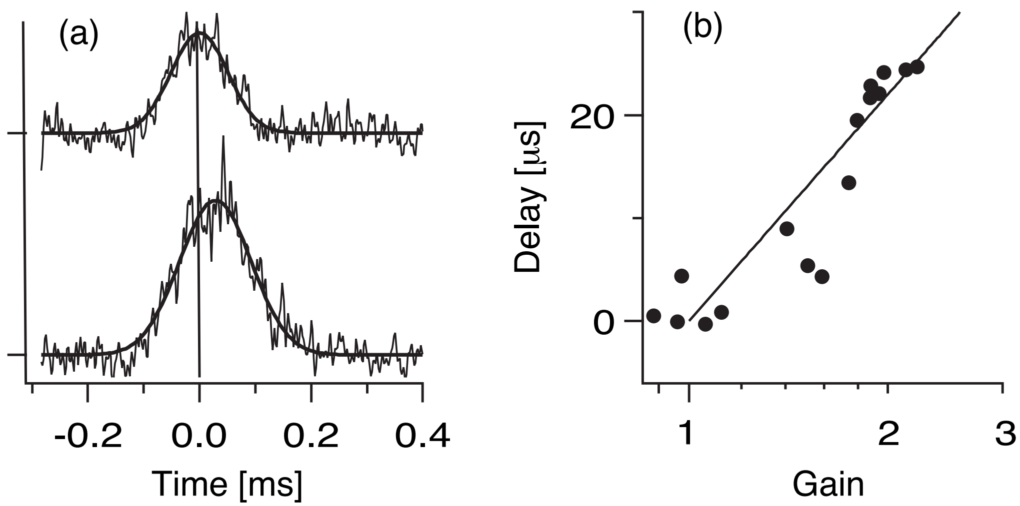


FIG. 3. Pulse delay due to light amplification. (a) About 20 ms delay was observed when a Gaussian pulse of about 140 ms width and 0.11 mW/cm^2 peak intensity was sent through the dressed condensate (bottom trace). The top trace is a reference taken without the dressed condensate. Solid curves are Gaussian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

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

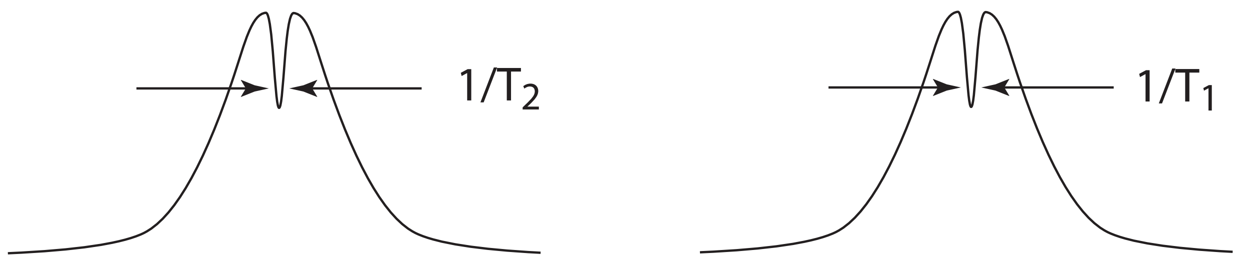
Recall that $n_g = n + \omega(dn/d\omega)$. Need a large $dn/d\omega$. (How?)

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 $T_2 << T_1$.

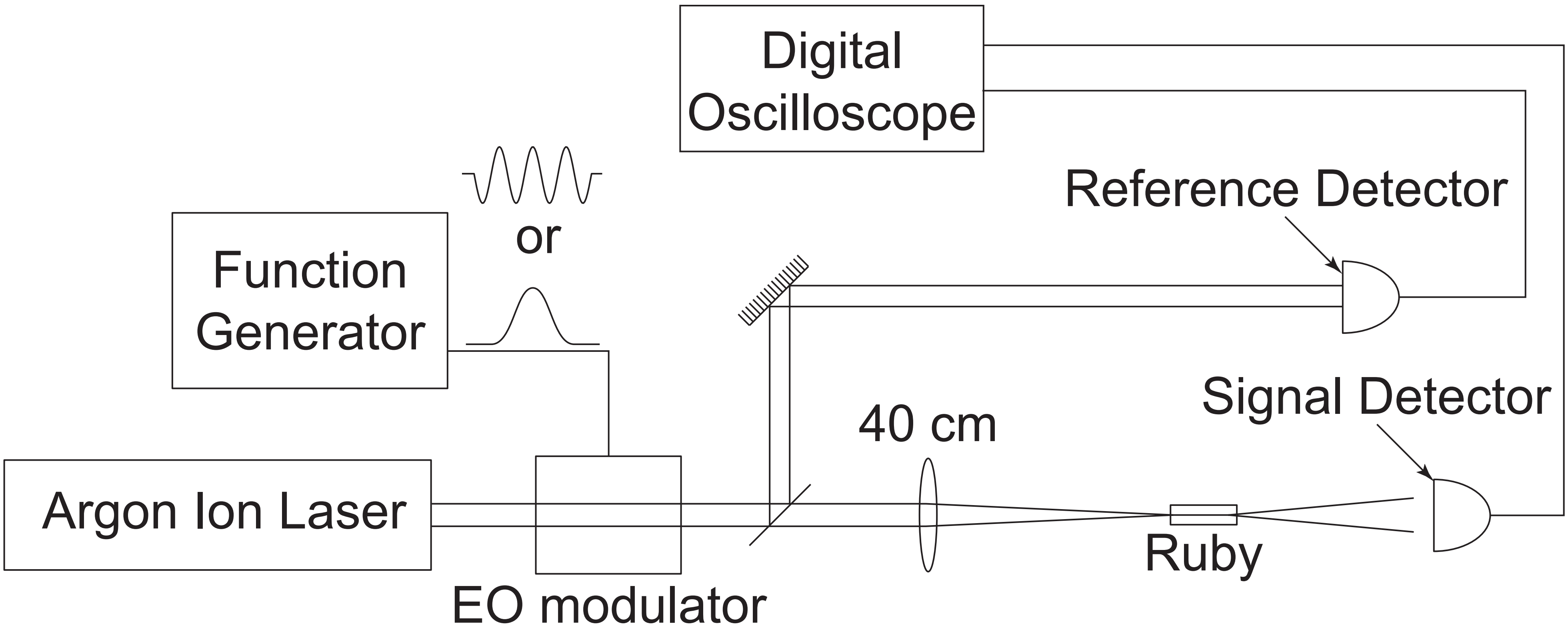


inhomogeneously broadened medium

homogeneously broadened medium (or inhomogeneously broadened)

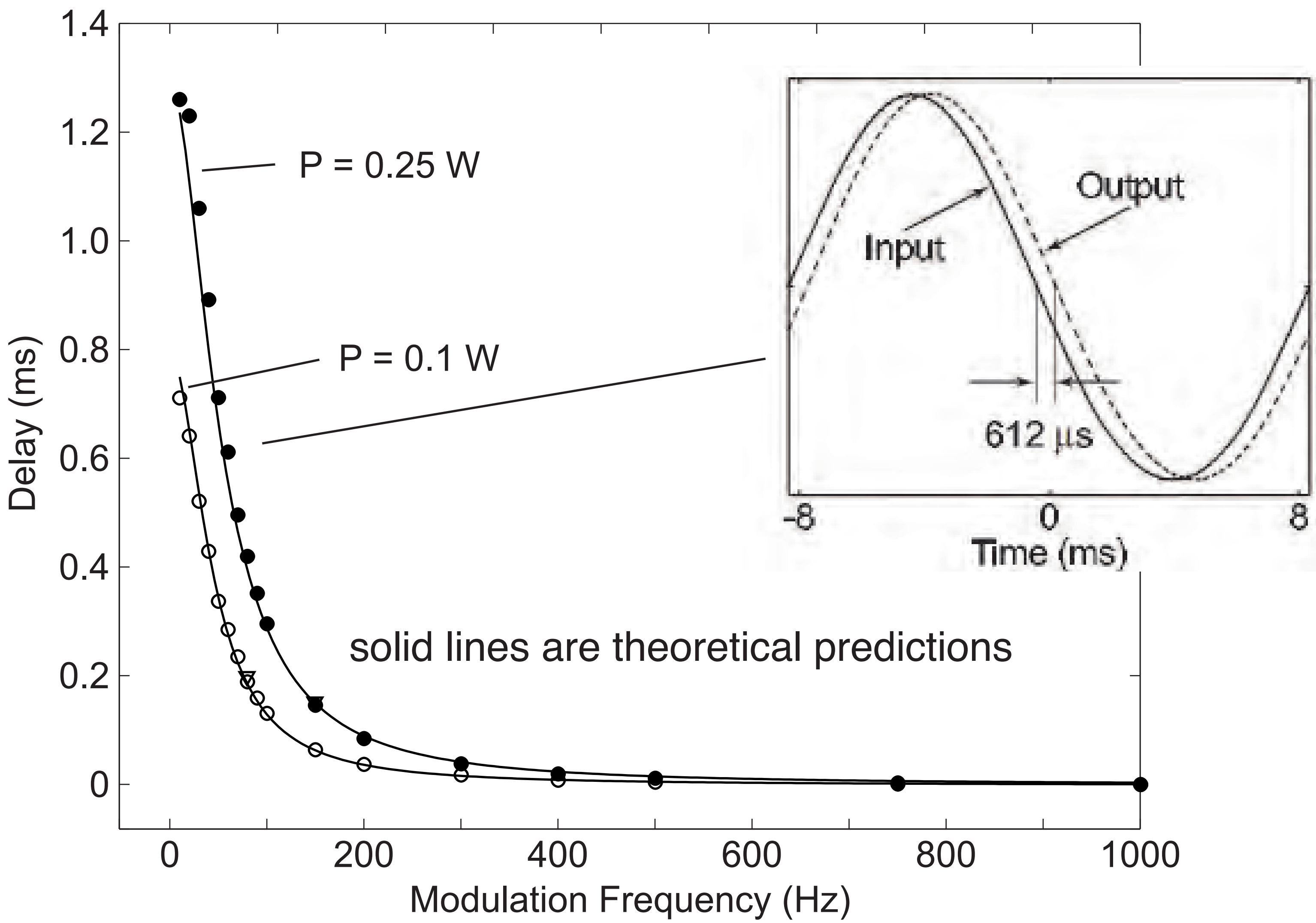
PRL 90,113903(2003).

Slow Light Experimental Setup



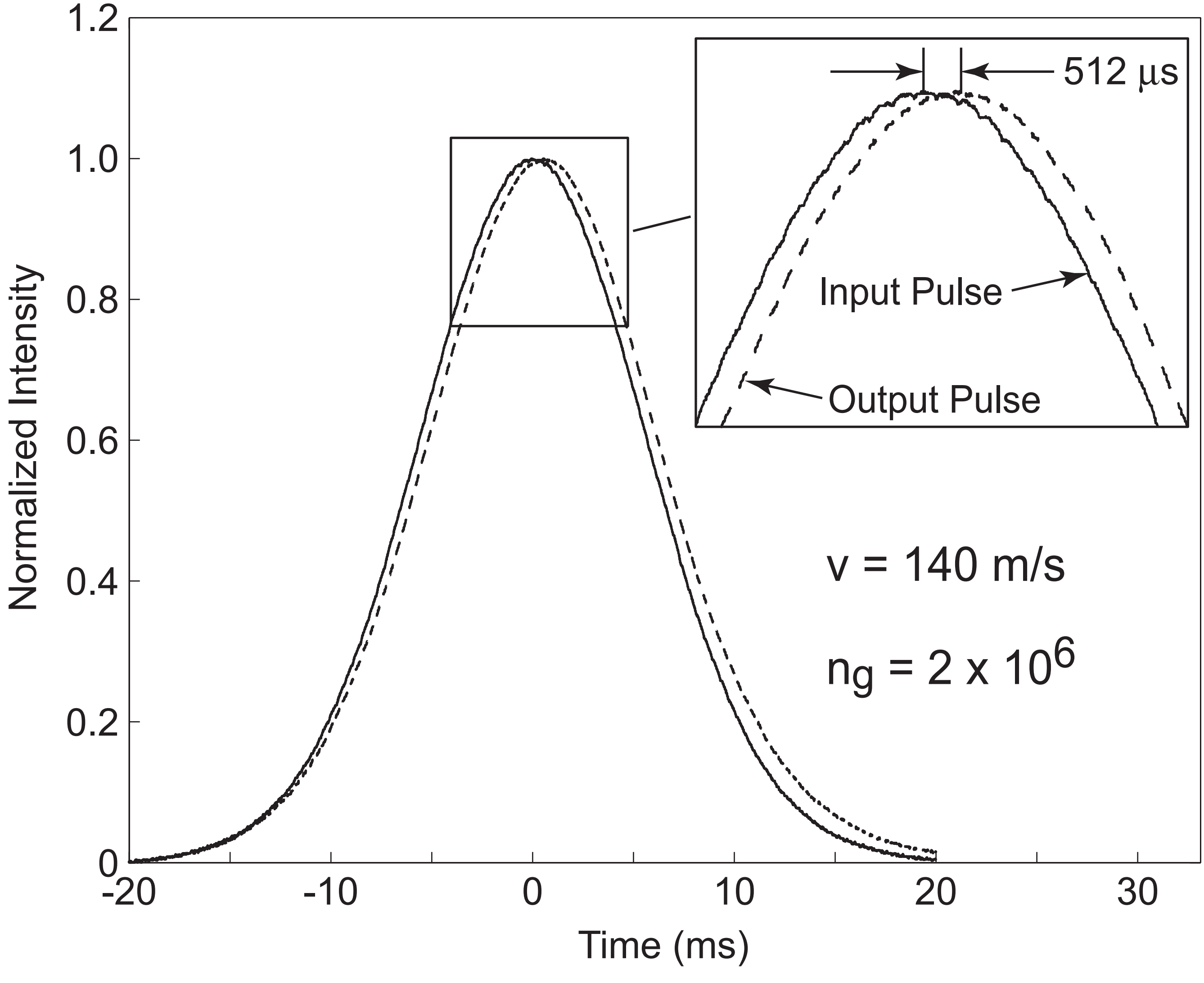
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



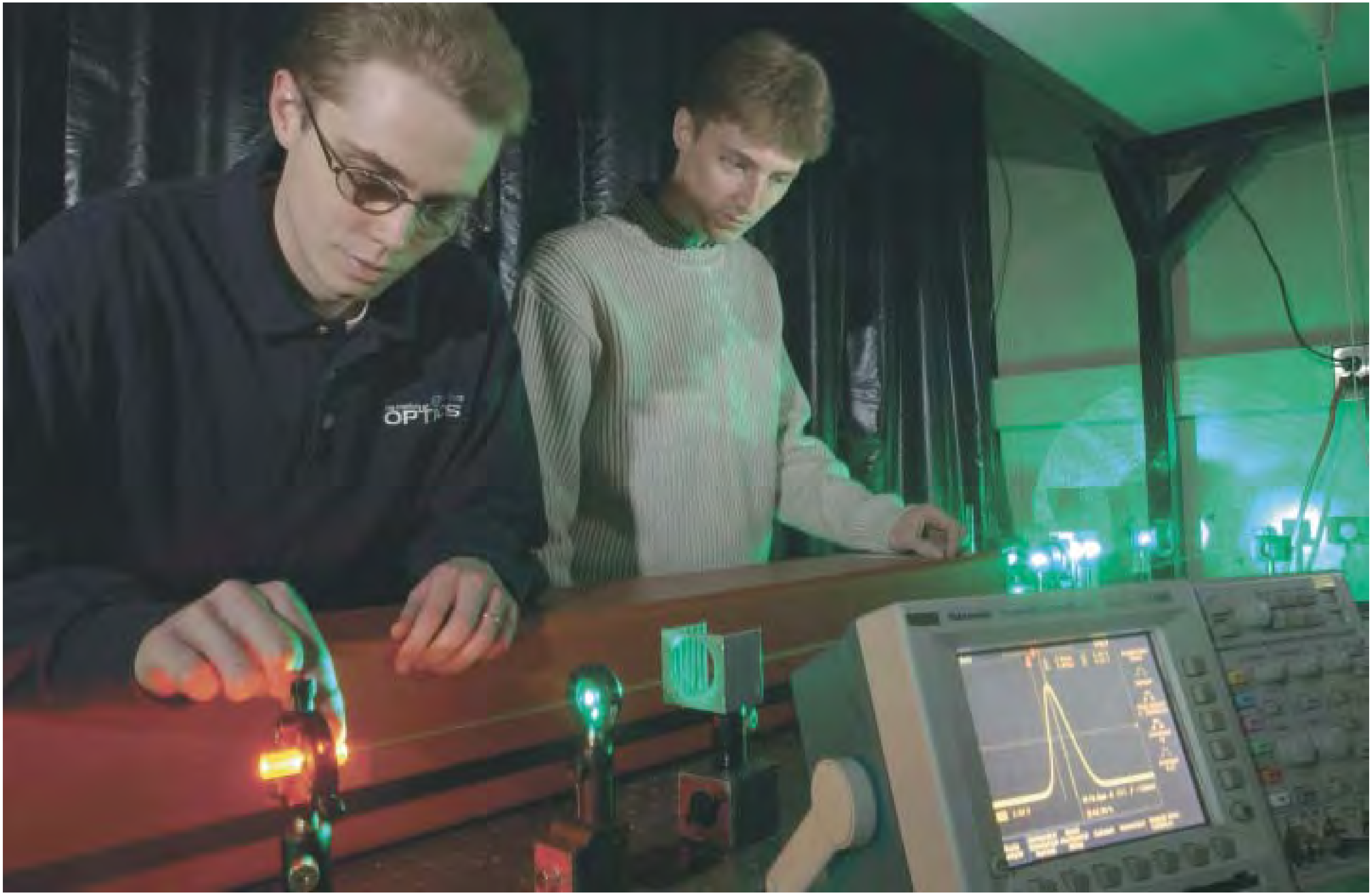
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

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

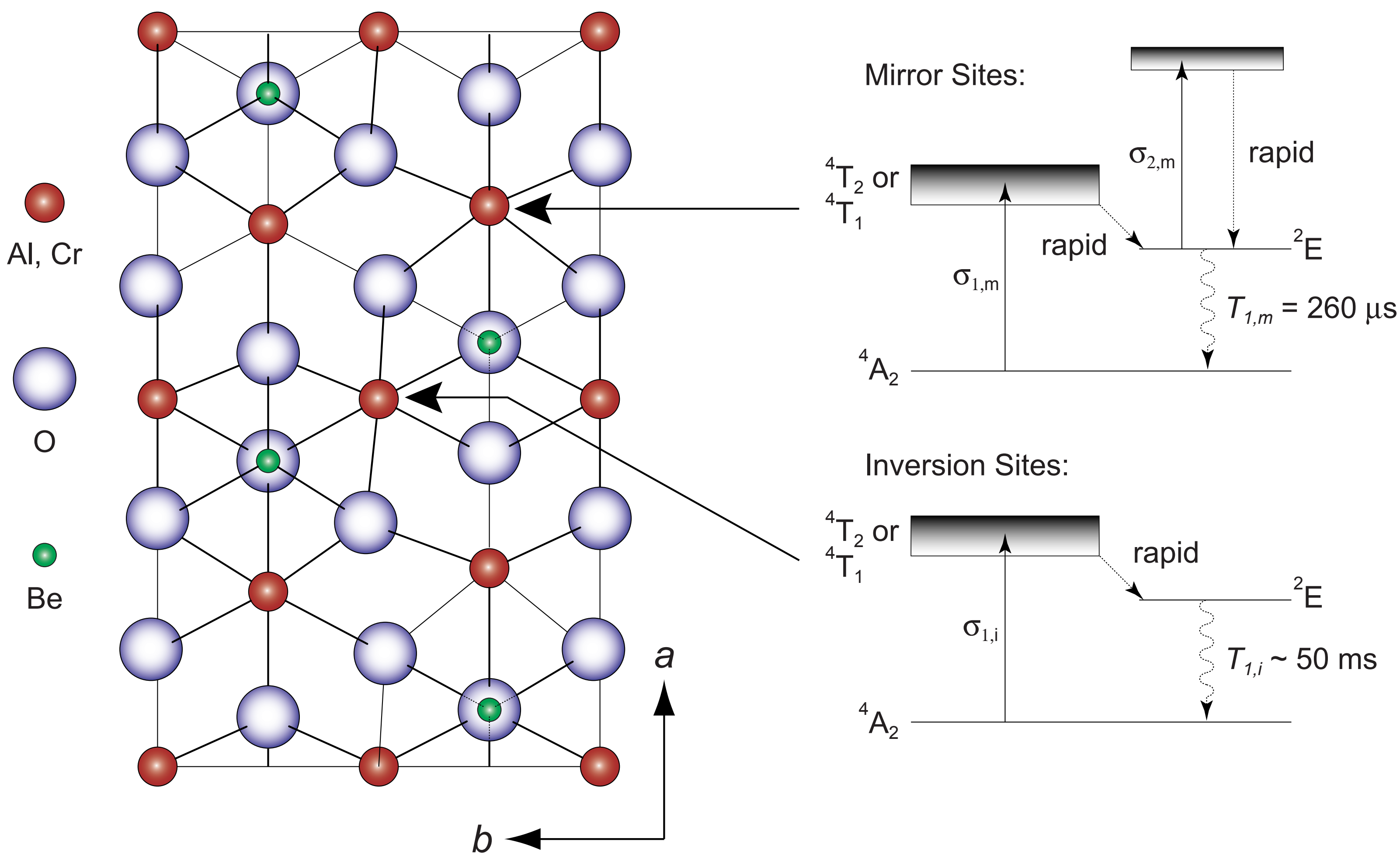
Laser need not be frequency stabilized

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

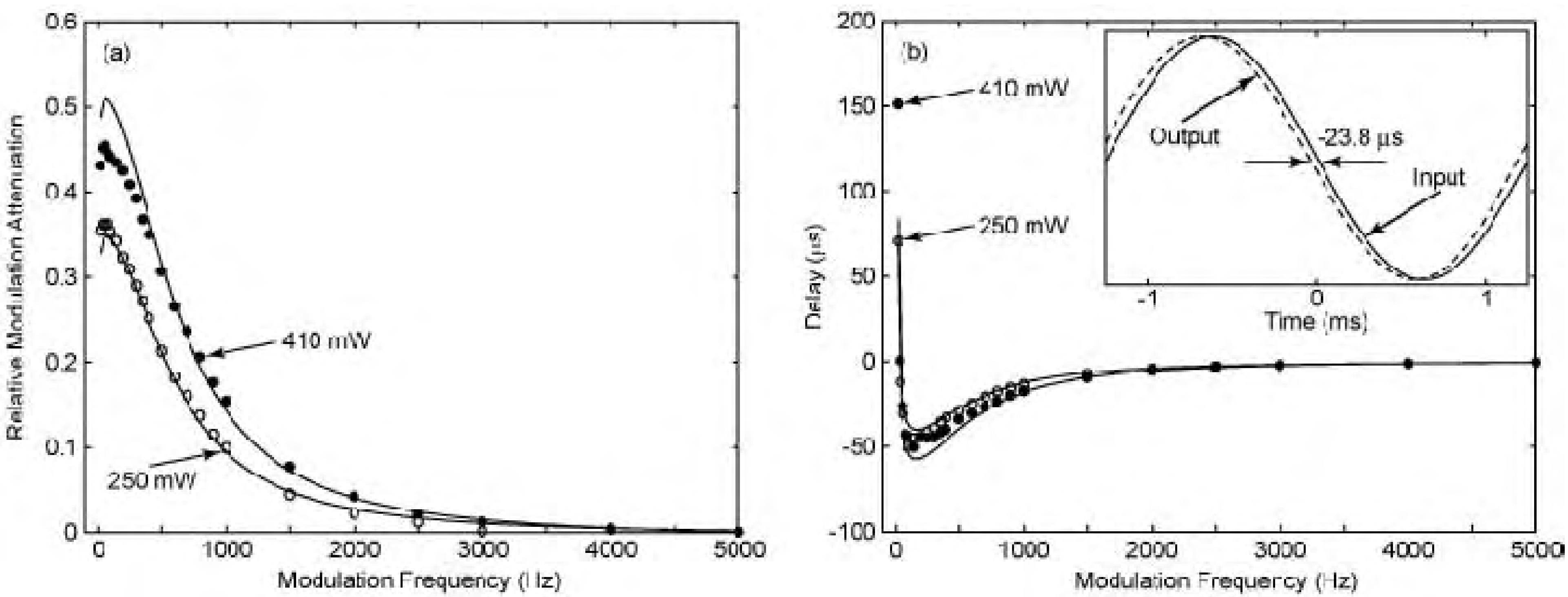


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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.

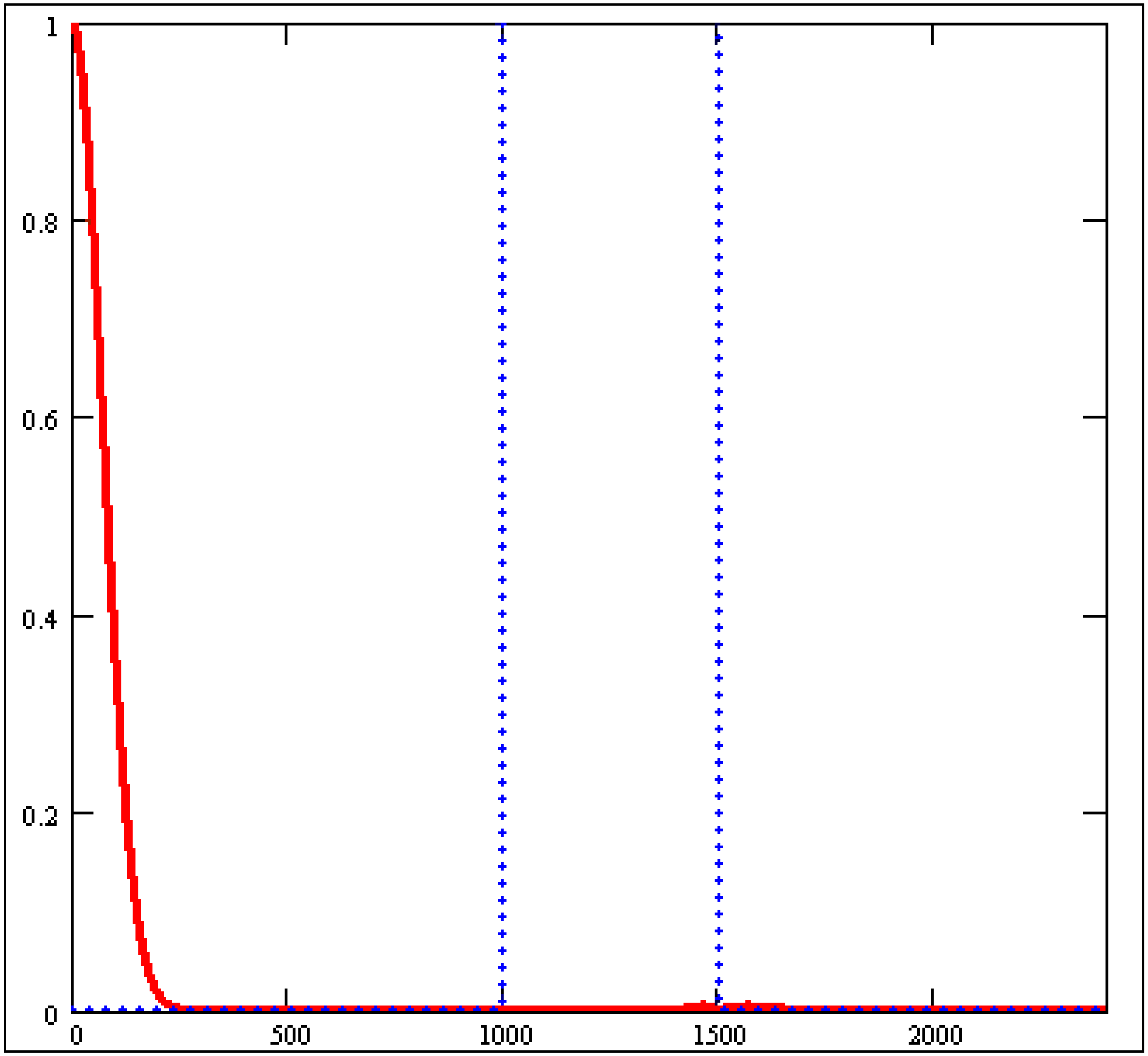
Study three cases:

Slow light $v_g = 0.5\ c$

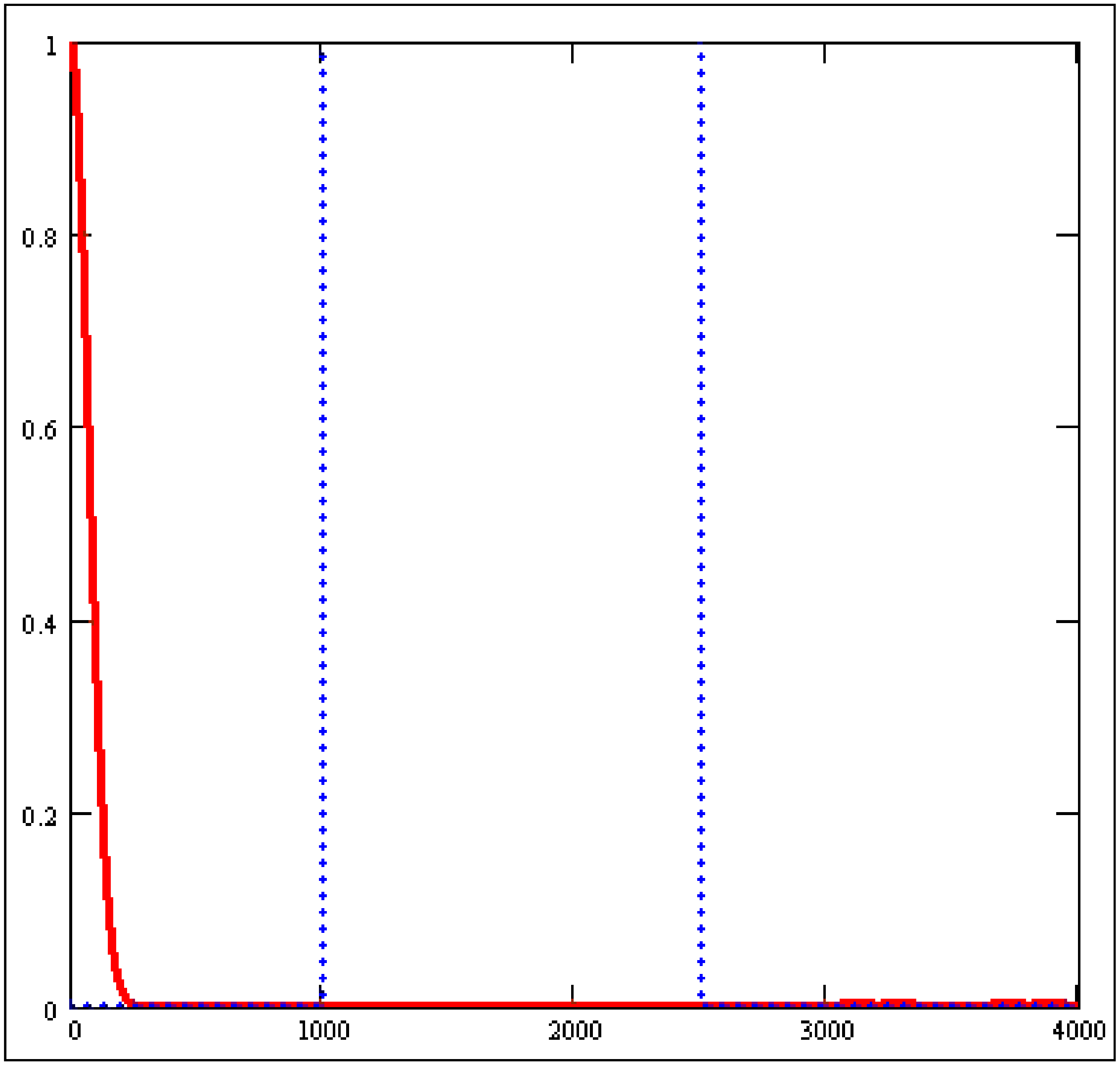
Fast light $v_g = 5\ c$ and $v_g = -2\ c$

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

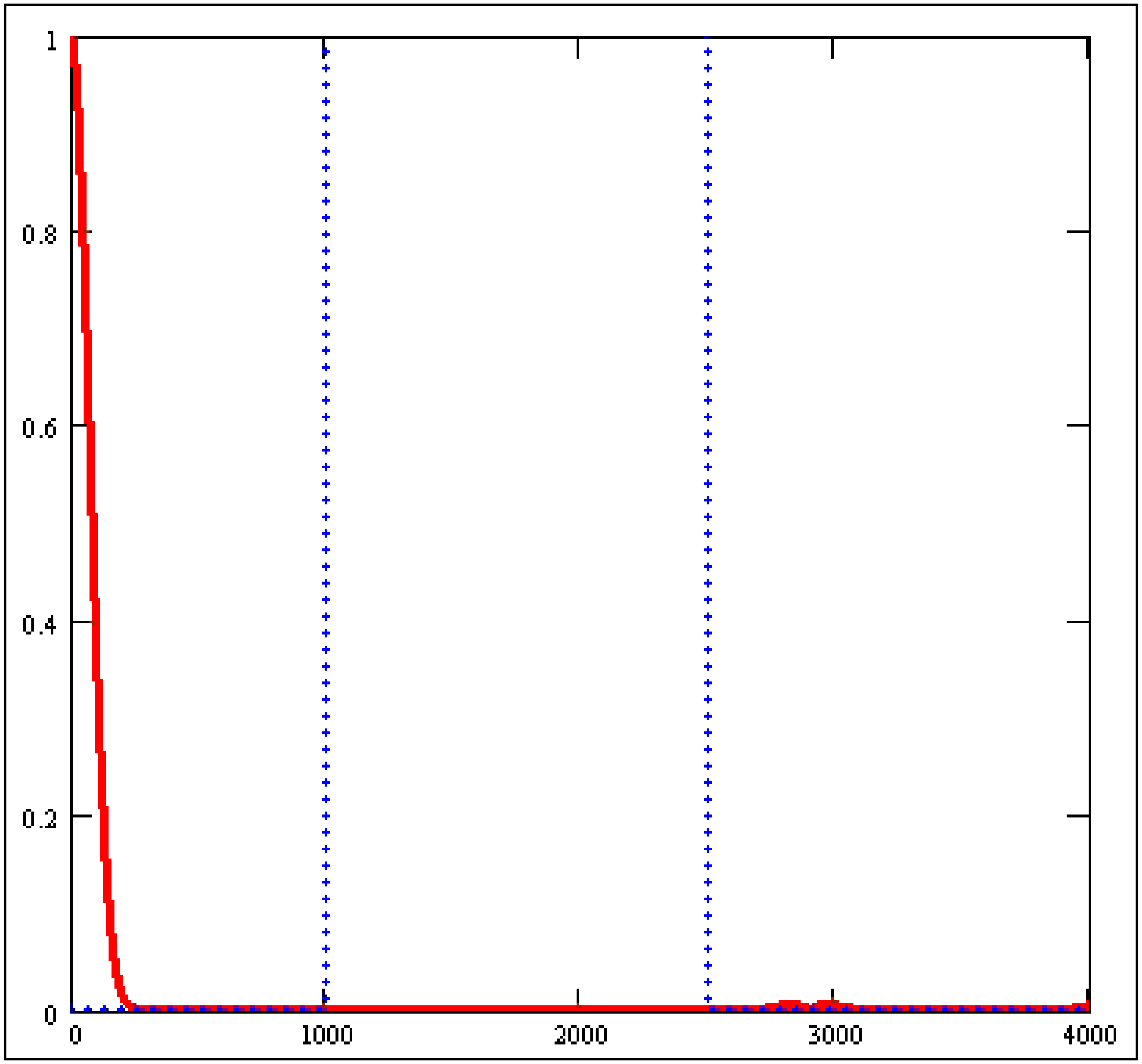
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



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

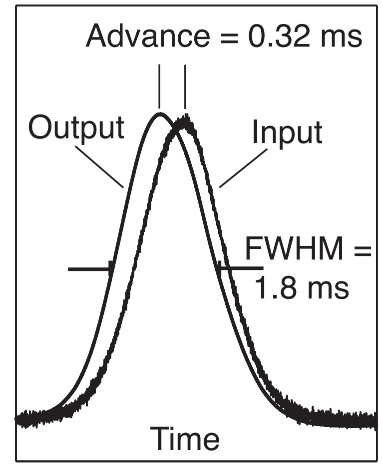


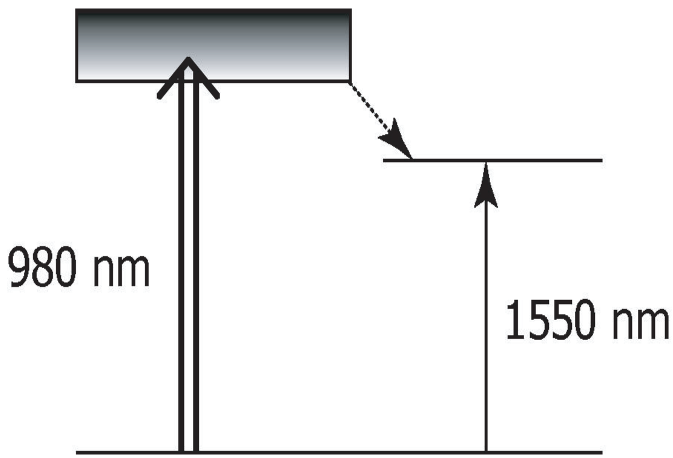
Pulse Propagation through a Fast-Light Medium (n_g = -.5, v_g = -2 c)

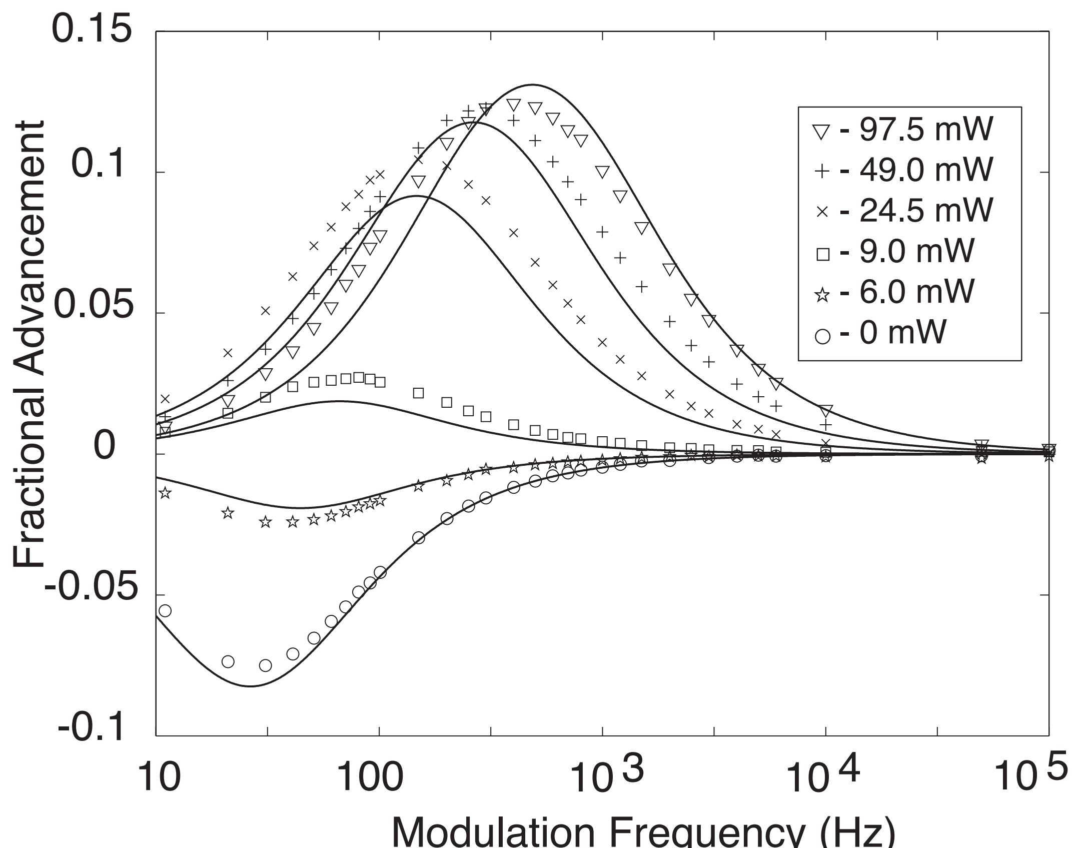


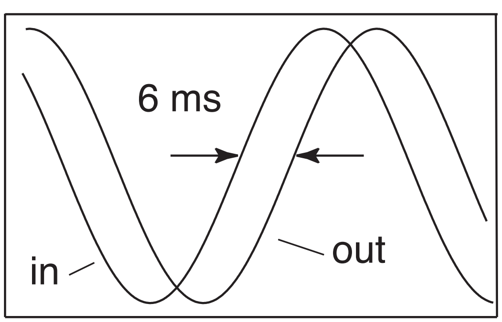
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



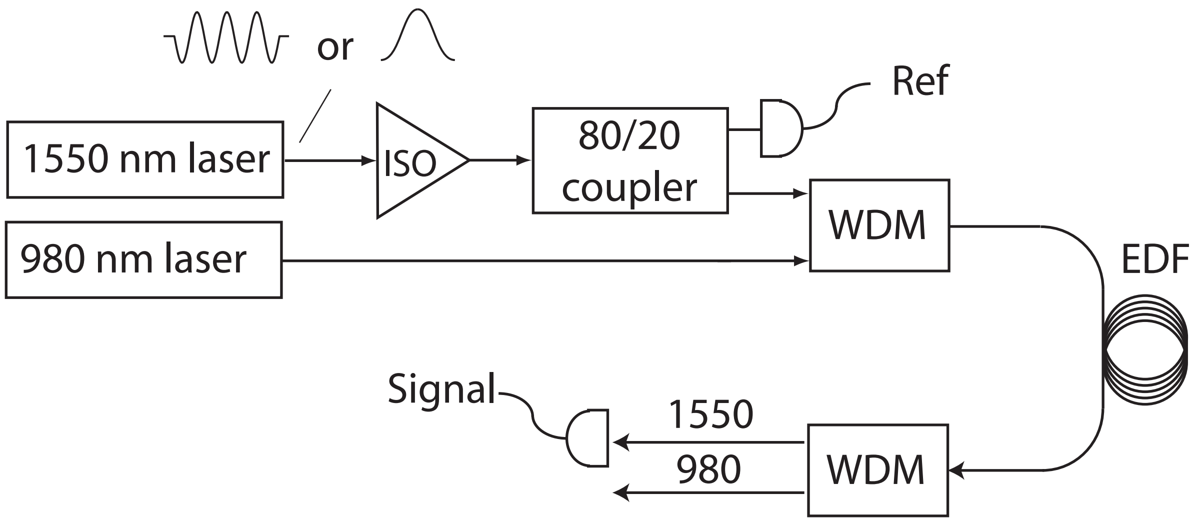






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

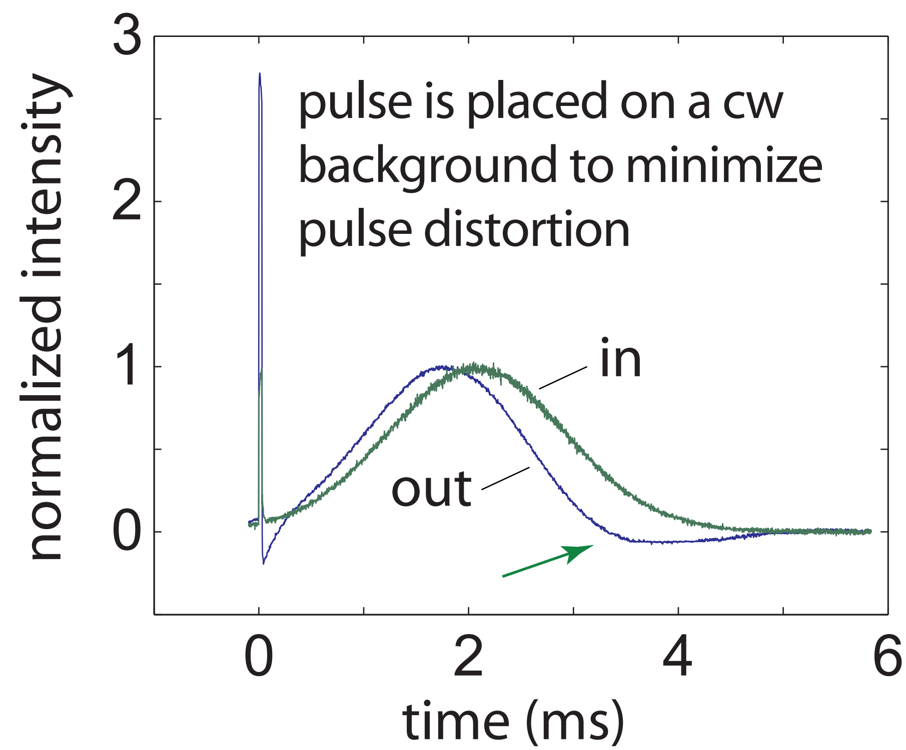
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



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

Procedure

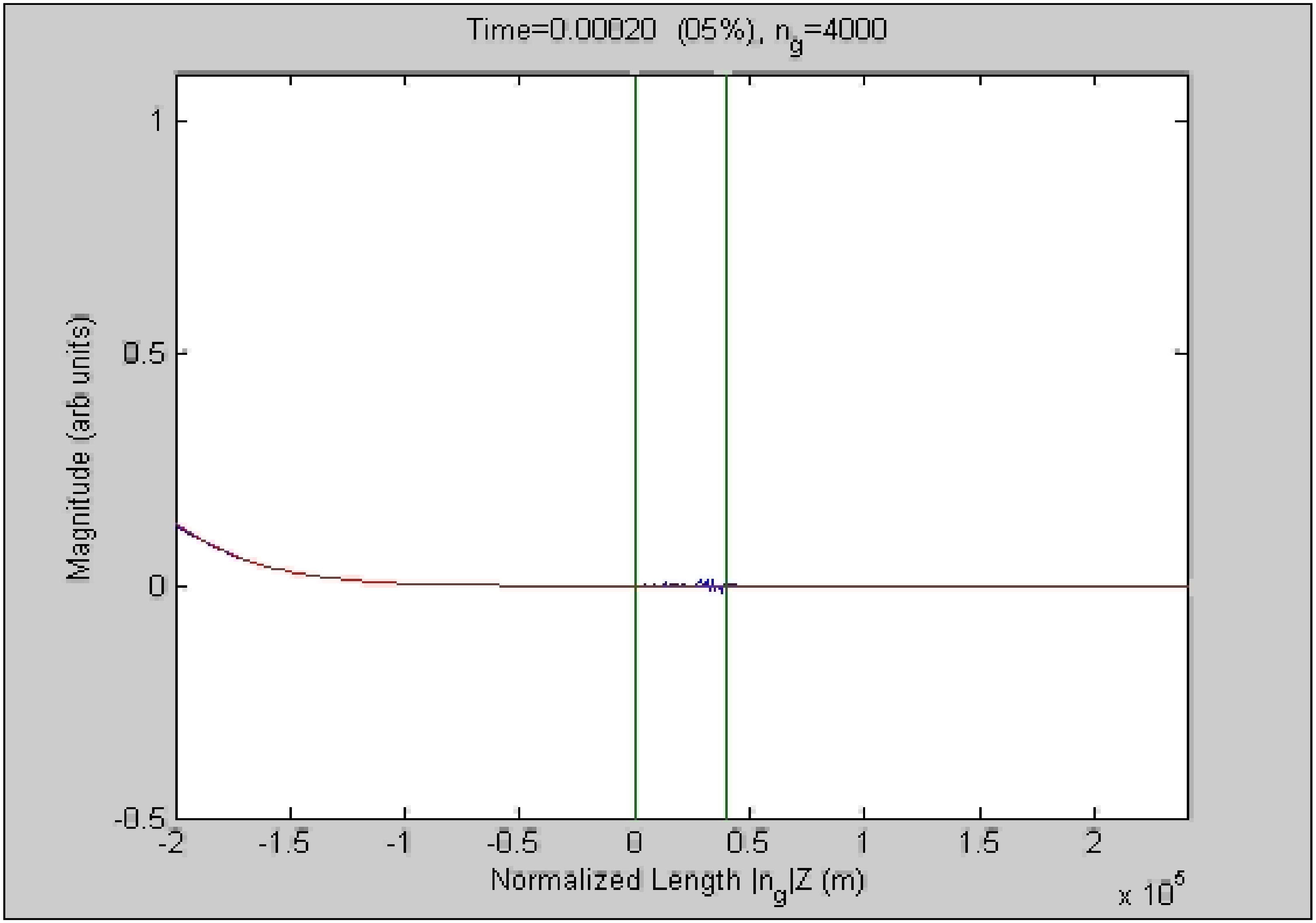
- cutback method
- couplers embedded in fiber



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)



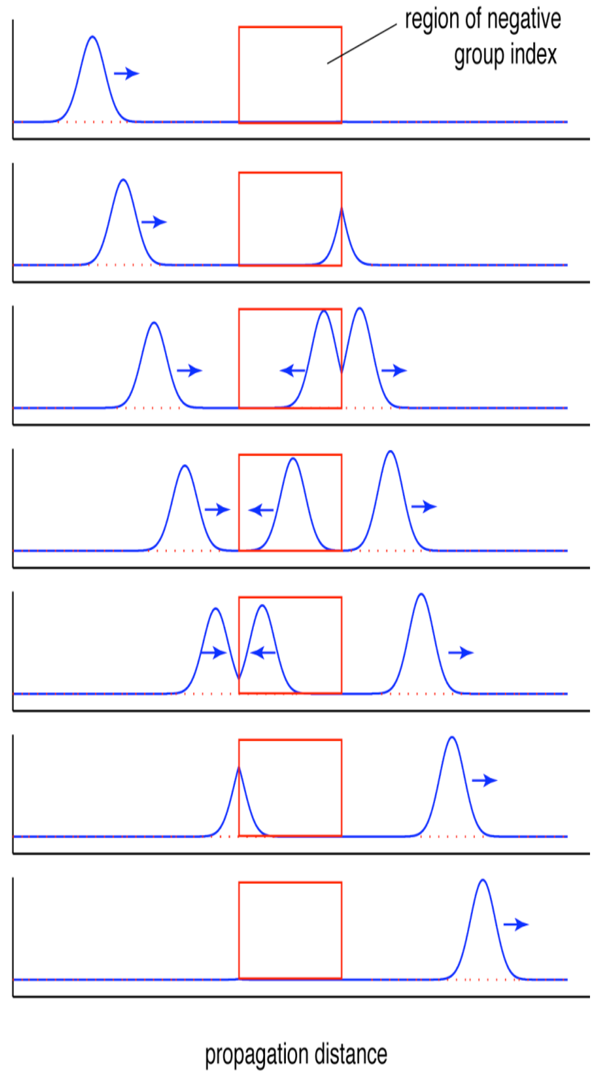
Observation of "Backwards" Pulse Propagation

- A strongly counterintuitive phenomenon

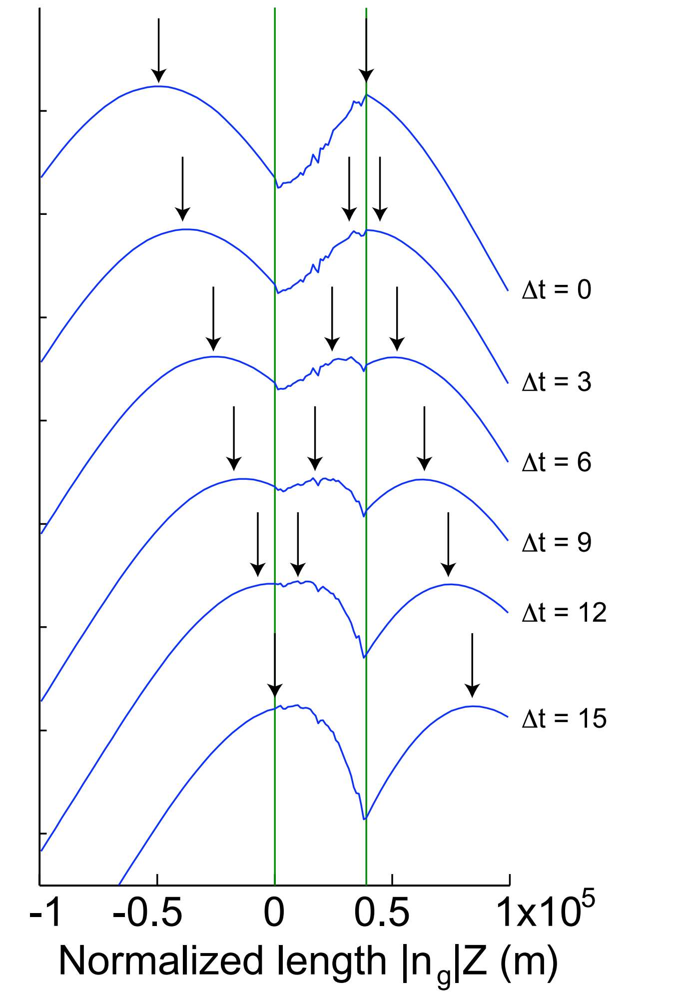
- But entirely consistent with established physics

- 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

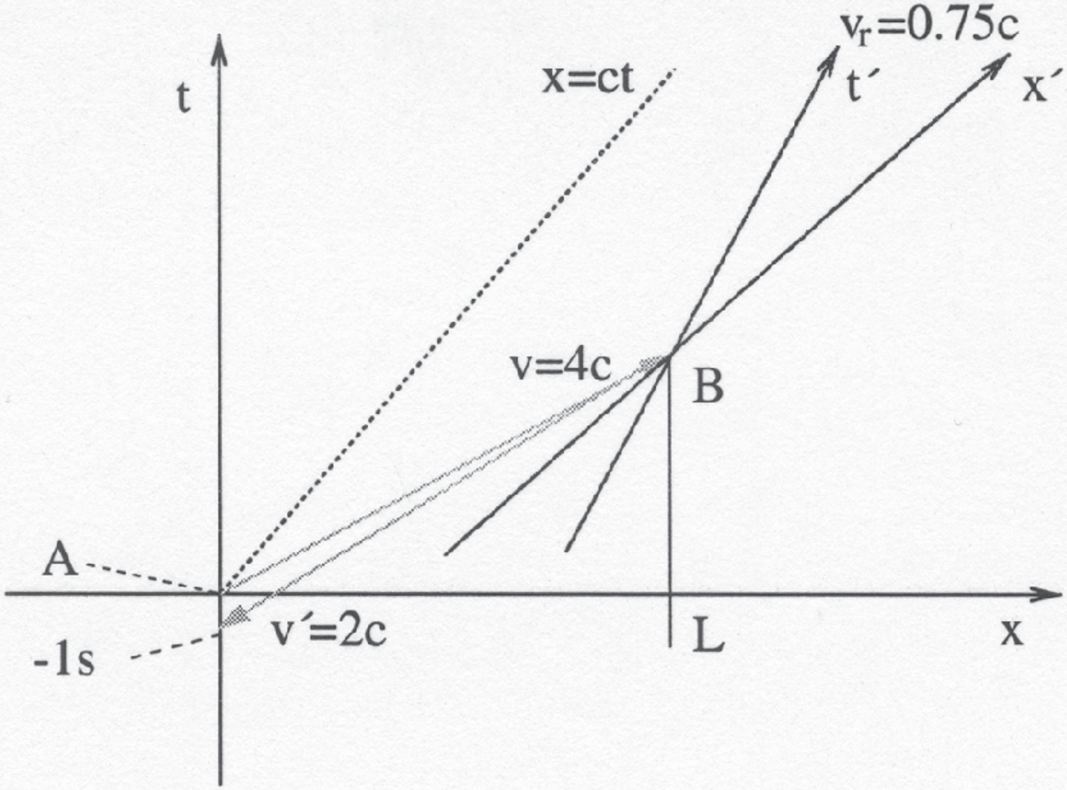
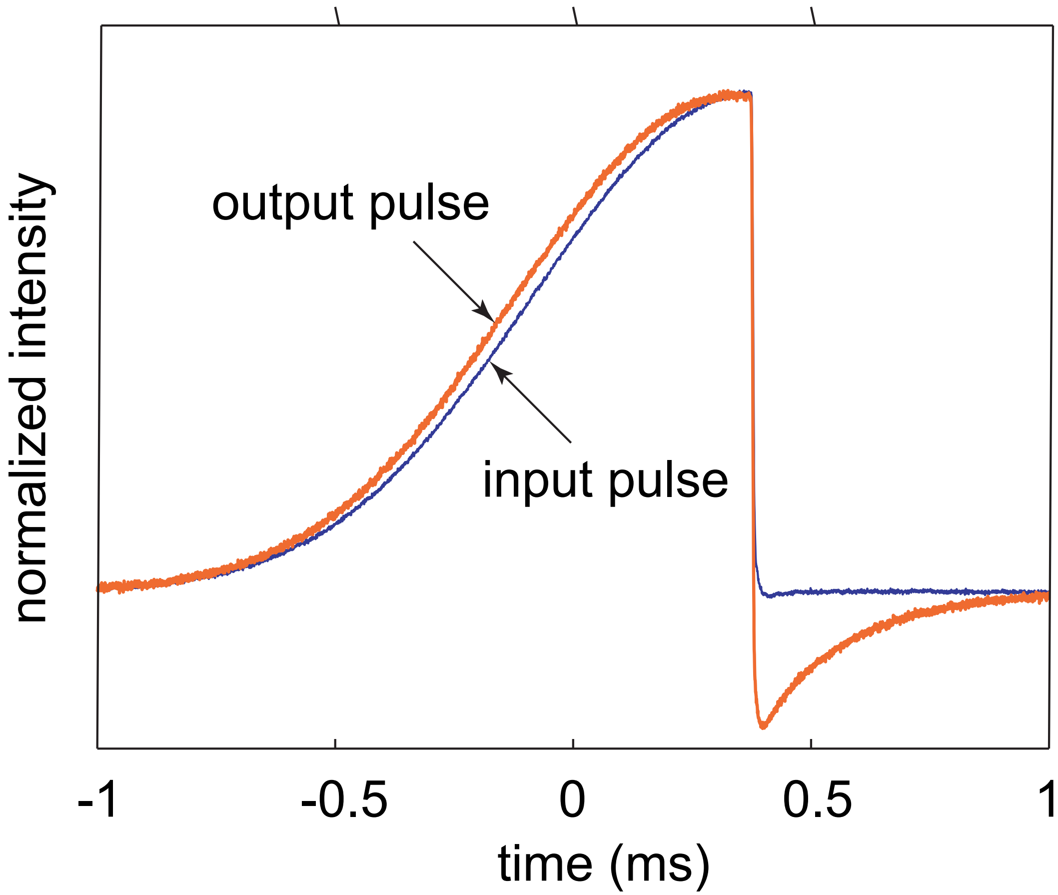


Fig. 6 Coordinates of two inertial observers **A** (0, 0) and **B** with $O(x, t)$ and $O'(x', t')$ moving with a relative velocity of 0.75*c*. The distance *L* between **A** and **B** is 2 000 000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v_s' = 2c$. The numbers in 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

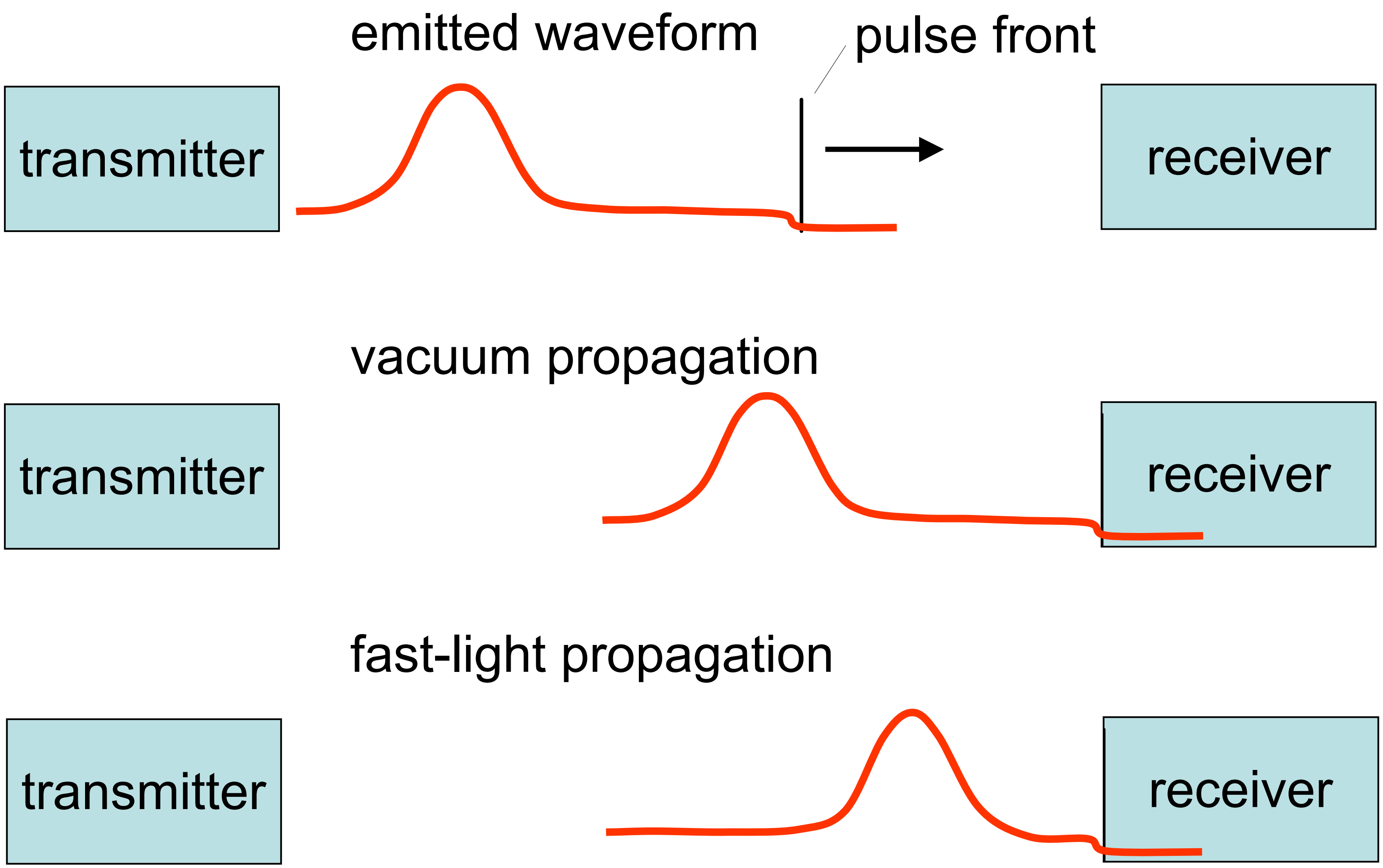
Discontinuity propagates at phase velocity

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.