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

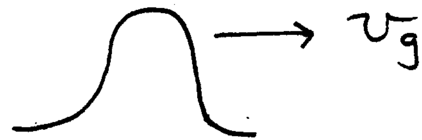
Implications for quantum information

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 $v_g = \frac{d\omega}{dk}$

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

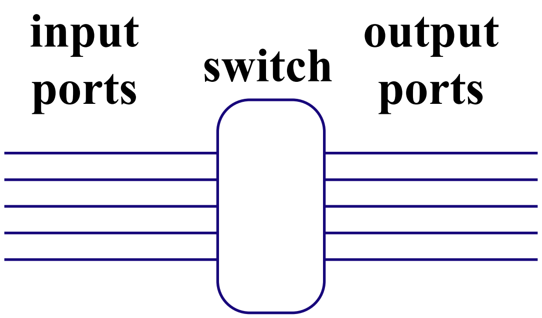
Thus

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

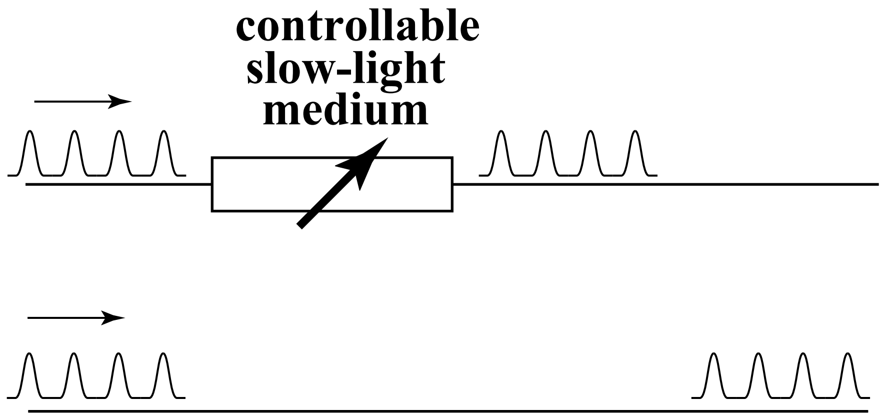
Thus $n_g \neq n$ in a dispersive medium!

Slow Light and Optical Buffers

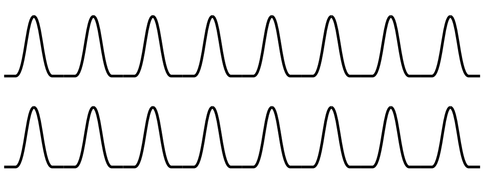
All-Optical Switch



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

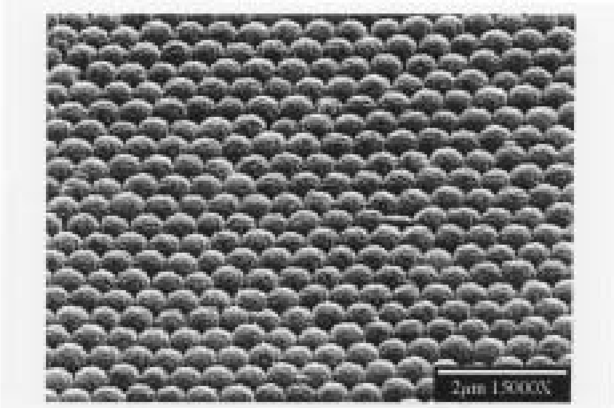
- Use the linear response of atomic systems

  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

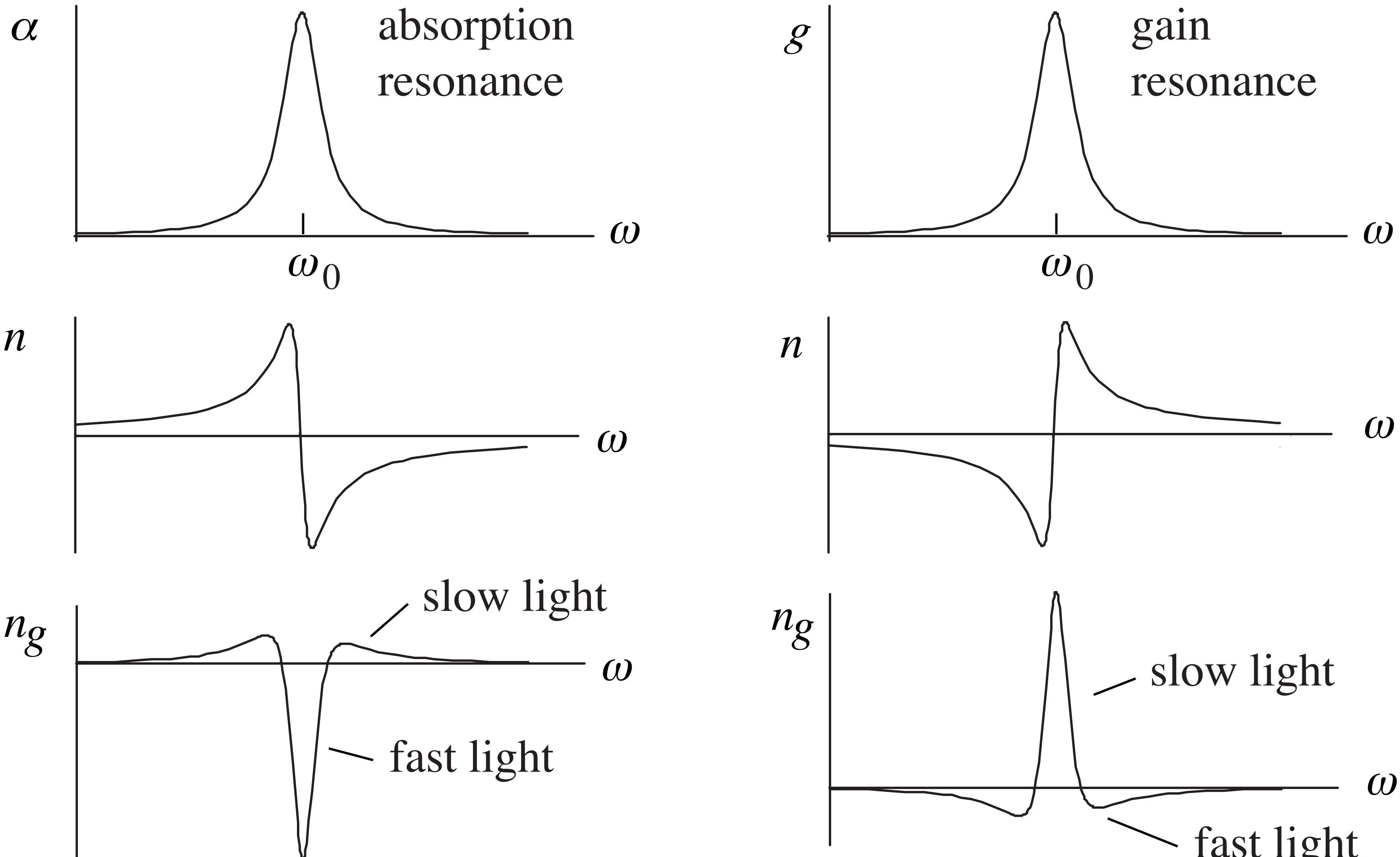
$$v_g = \frac{c}{n_g} \qquad\qquad n_g = n + \omega \frac{dn}{d\omega}$$

Want large dispersion to obtain extreme group velocities

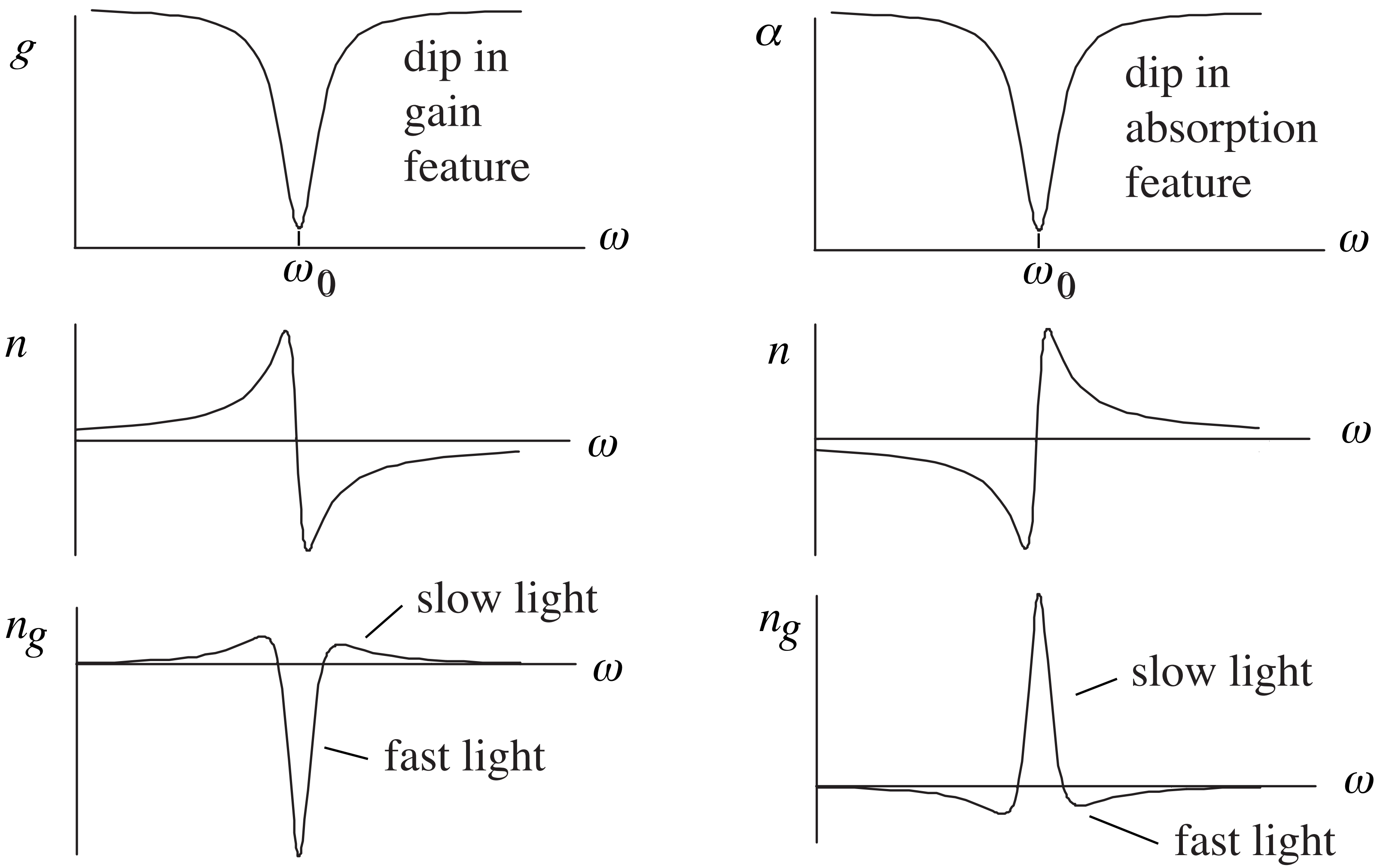
Sharp spectral features produce large dispersion.

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

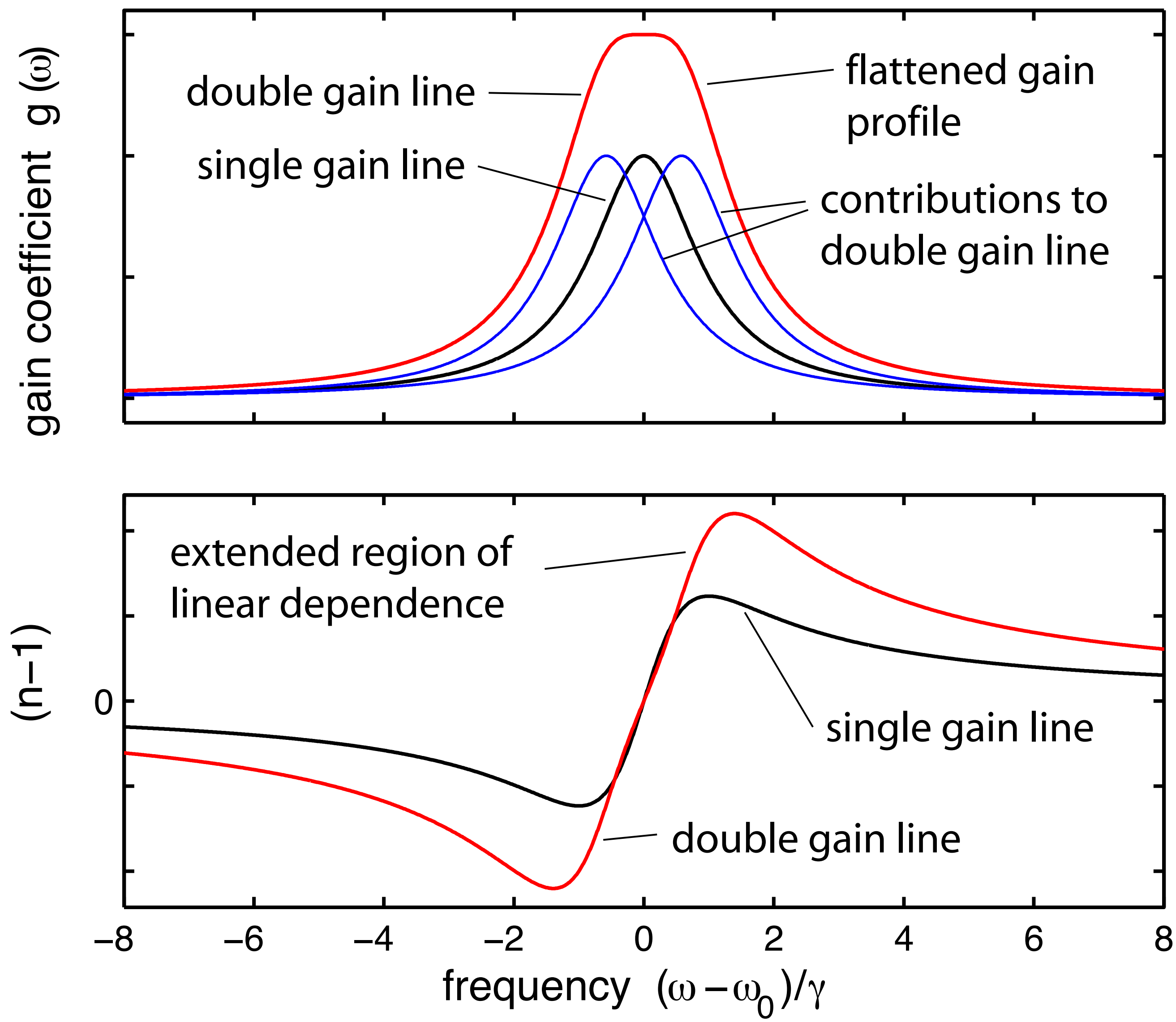


How to Create Slow and Fast Light II – Use Dip in Gain or Absorption Feature



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*§

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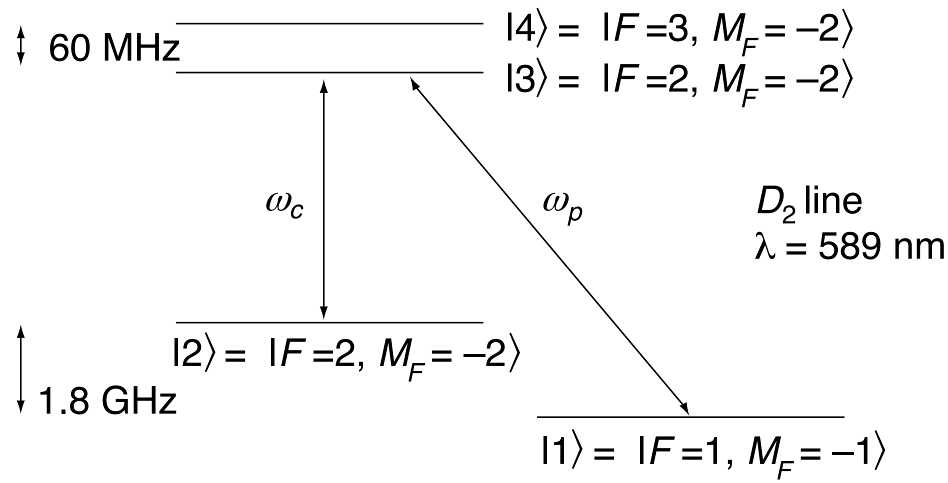
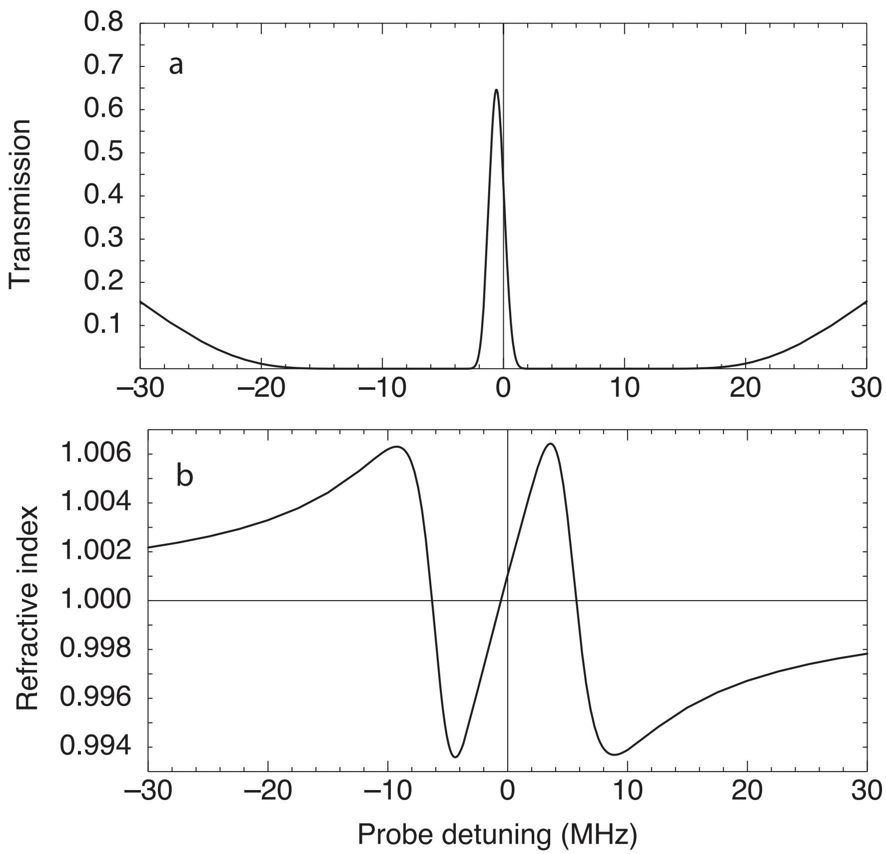
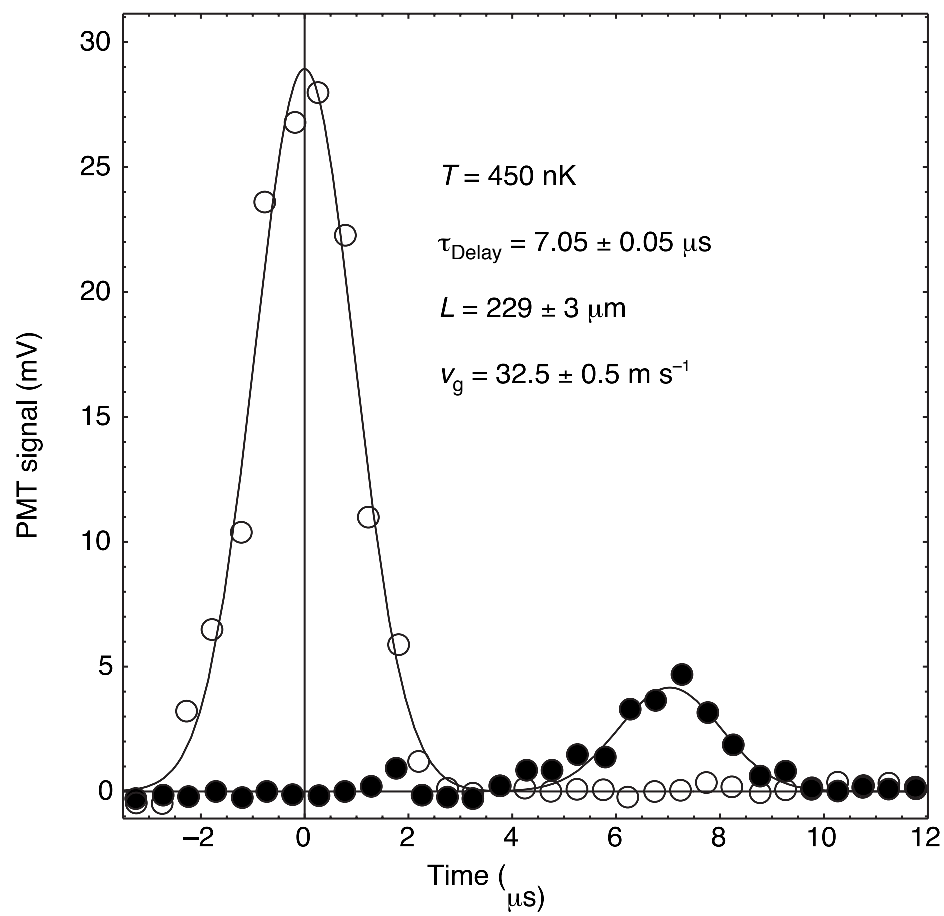
[2] Department of Physics, § Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

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

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





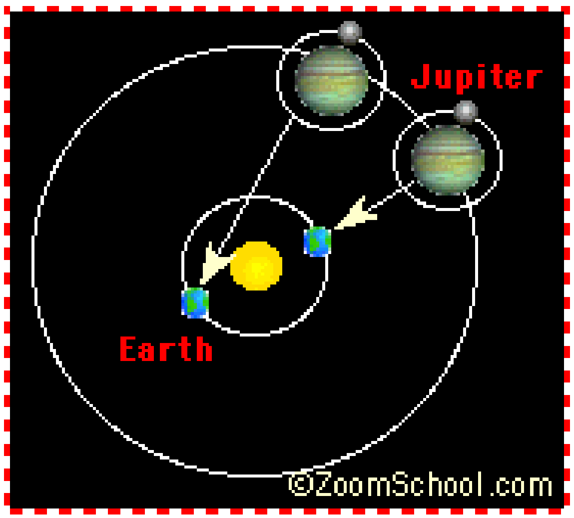


Determination of the Velocity of Light*

"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

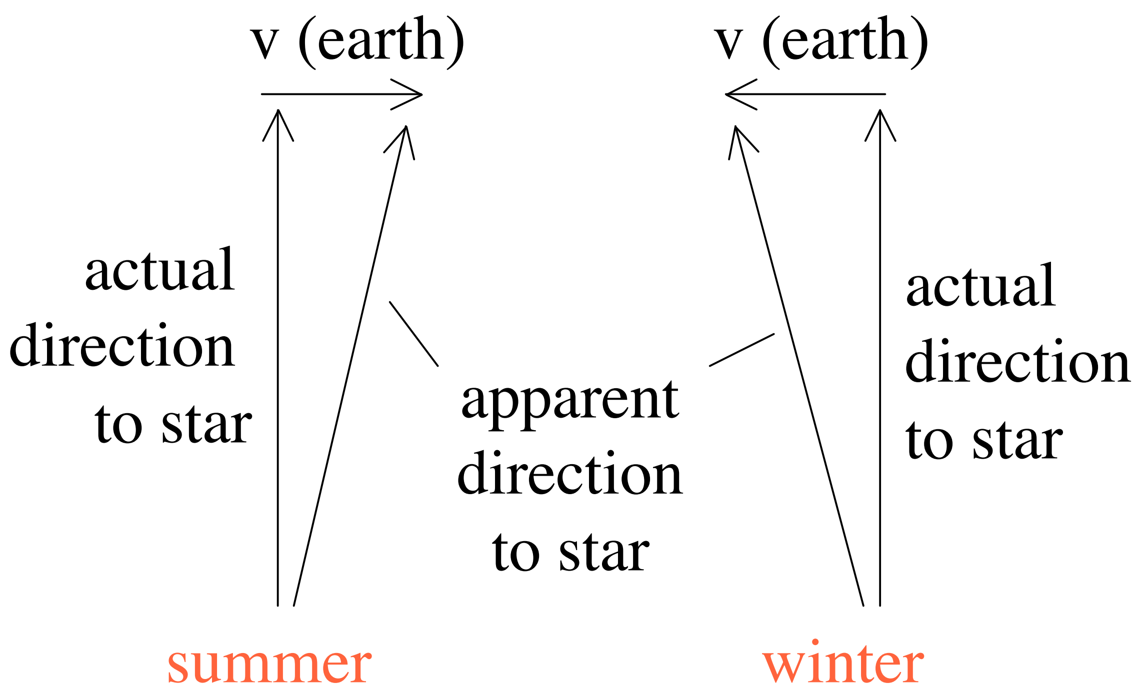
(Actually, light transit time from sun to earth is just over 8 minutes, and c = 299,793 km/sec)

*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.



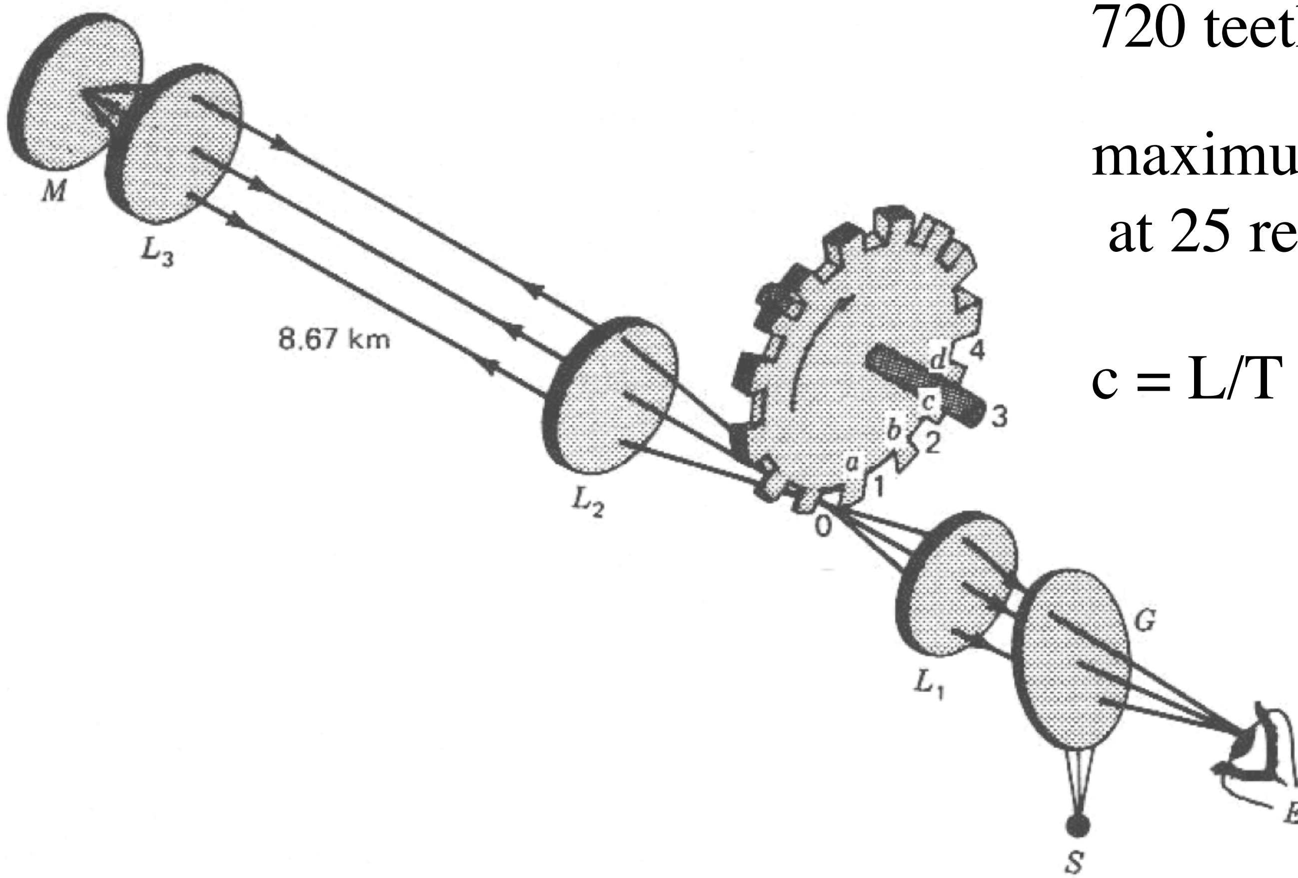
$$v(\text{earth}) \approx 30\ \text{km/s}$$

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

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

Determination of the Velocity of Light
Laboratory Methods

Fizeau (1849) Time-of-flight method



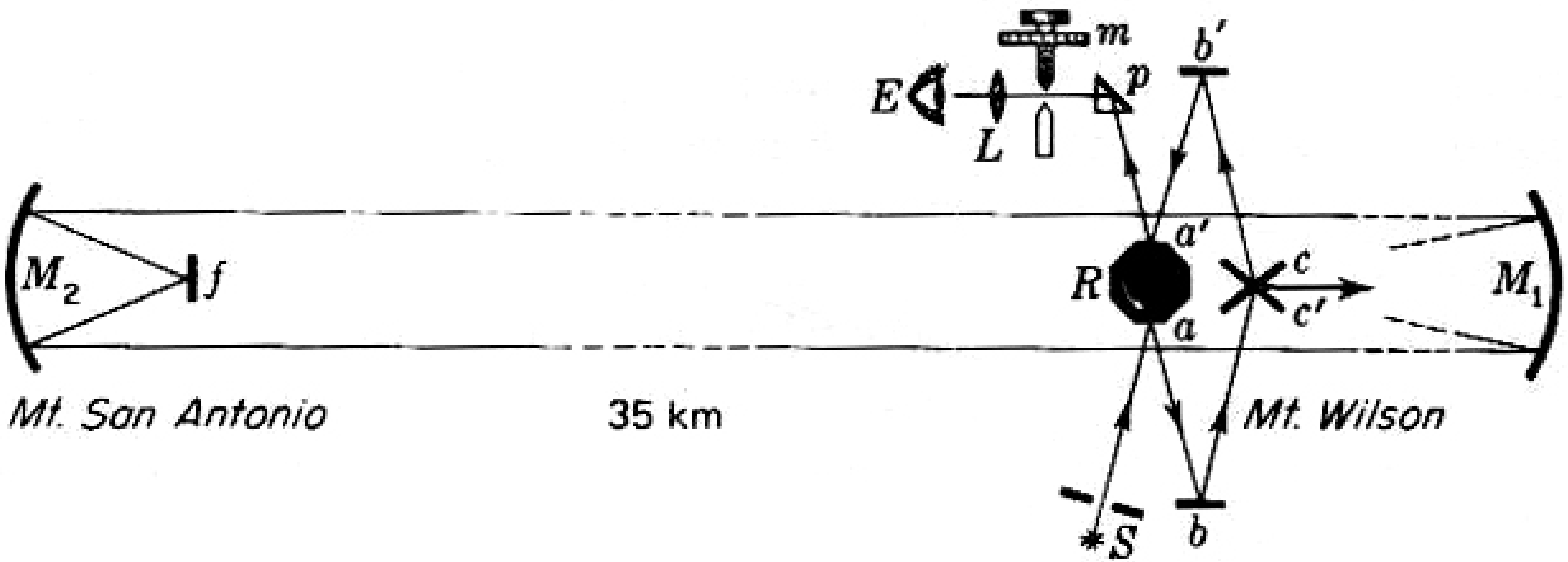
720 teeth in wheel

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.



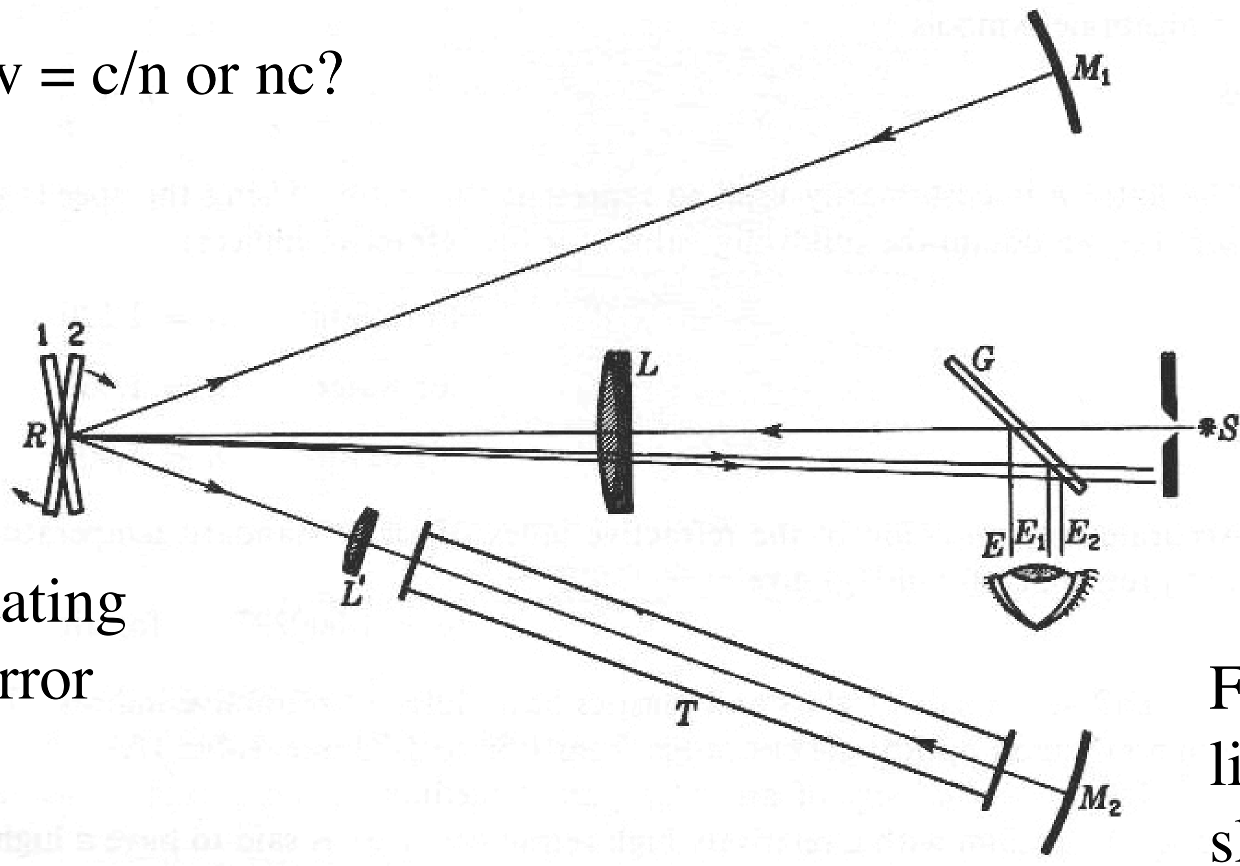
Rotating octagonal mirror

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?



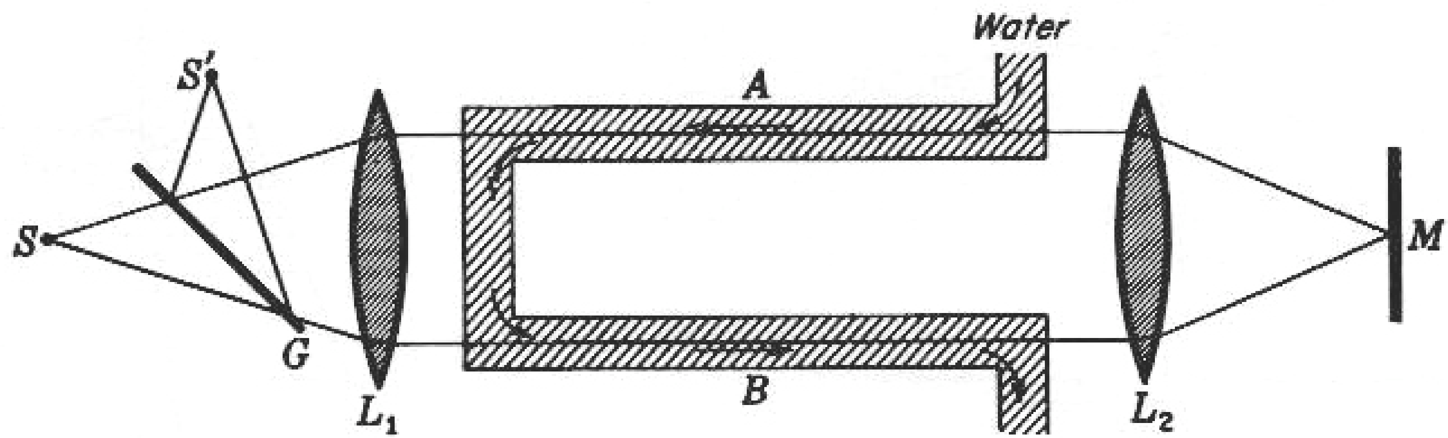
rotating mirror

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)

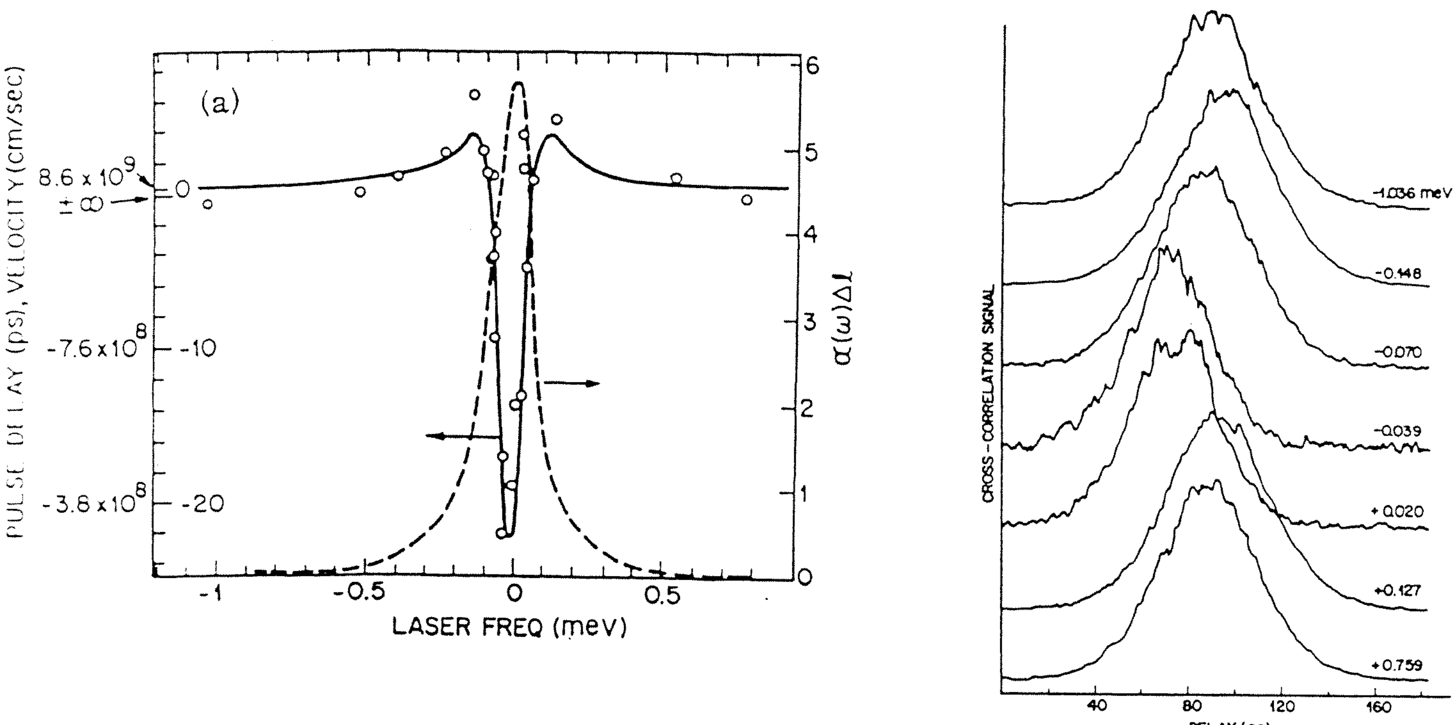
The frequency and wavelength of the methane-stabilized laser at 3.39 μm were directly measured against the respective primary standards. With infrared frequency synthesis techniques, we obtain $\nu = 88.376\,181\,627(50)$ THz. With frequency-controlled interferometry, we find $\lambda = 3.392\,231\,376(12)$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

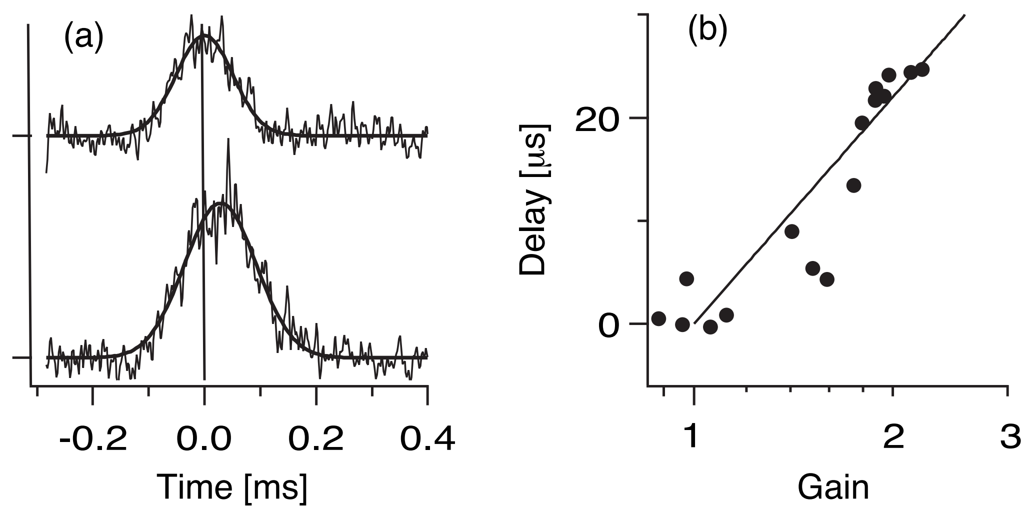


FIG. 3. Pulse delay due to light amplification. (a) About 20 ms delay was observed when a Gaussian pulse of about 140 ms width and 0.11 mW/cm^2 peak intensity was sent through the dressed condensate (bottom trace). The top trace is a reference taken without the dressed condensate. Solid curves are Gaussian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

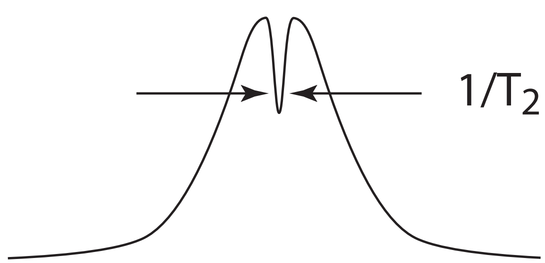
Kramers-Kronig relations:

Want a very narrow feature in absorption line.

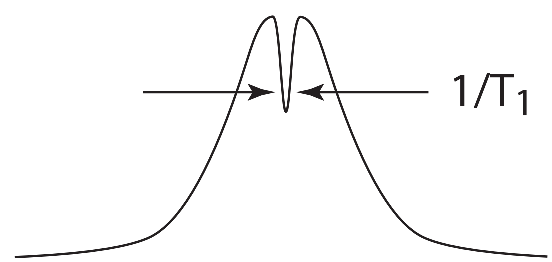
Well-known "trick" for doing so:

Make use of spectral holes due to population oscillations.

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



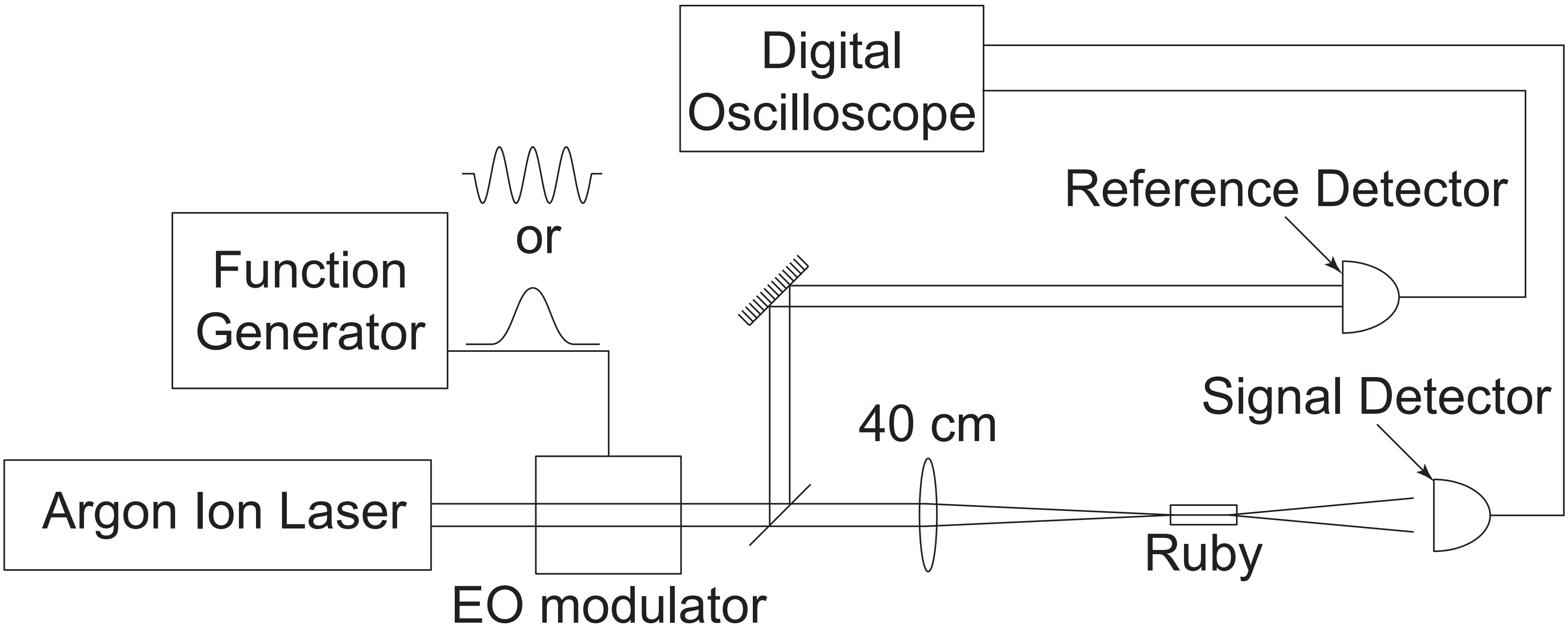
inhomogeneously broadened medium



homogeneously broadened medium (or inhomogeneously broadened)

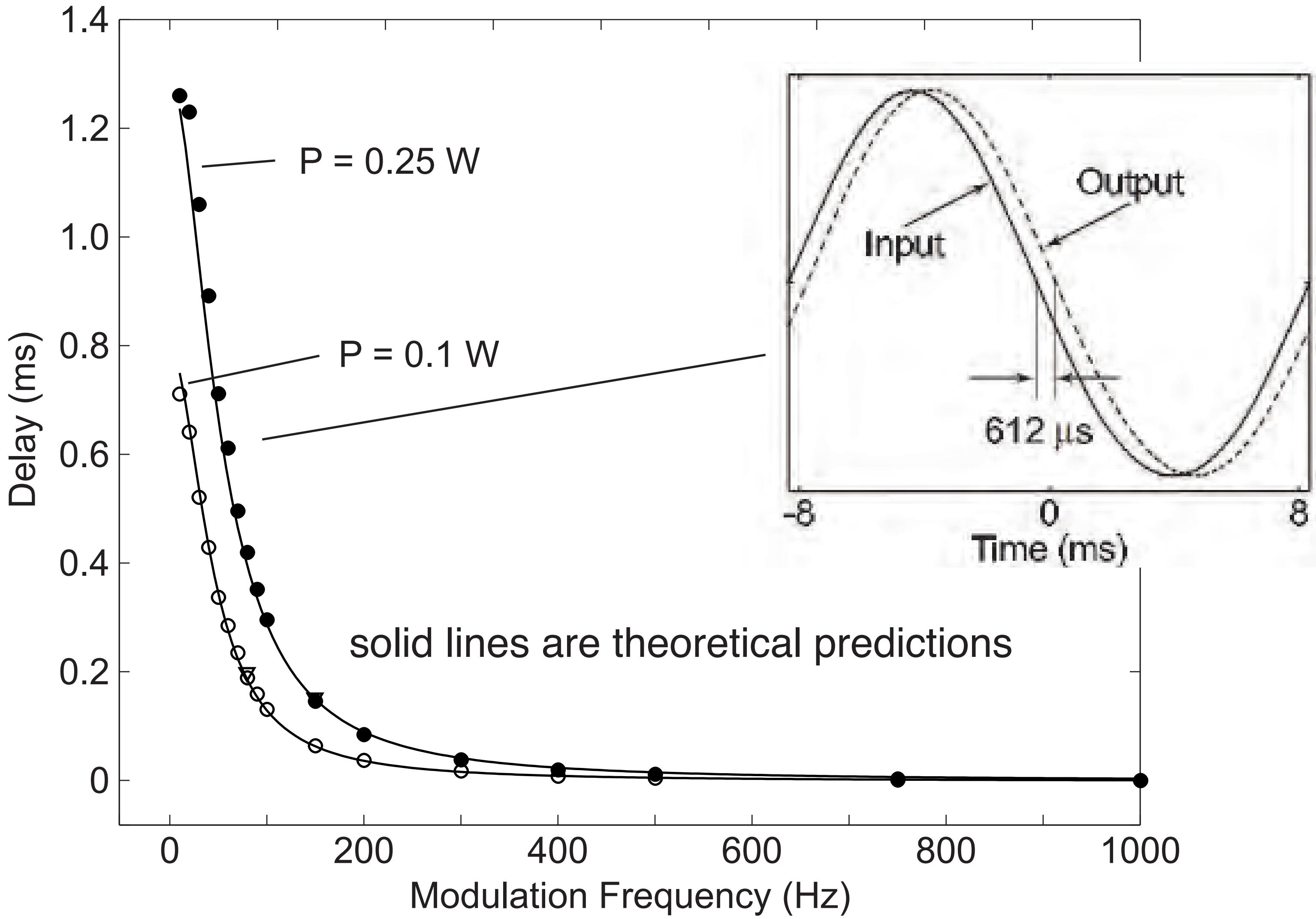
PRL 90,113903(2003).

Slow Light Experimental Setup



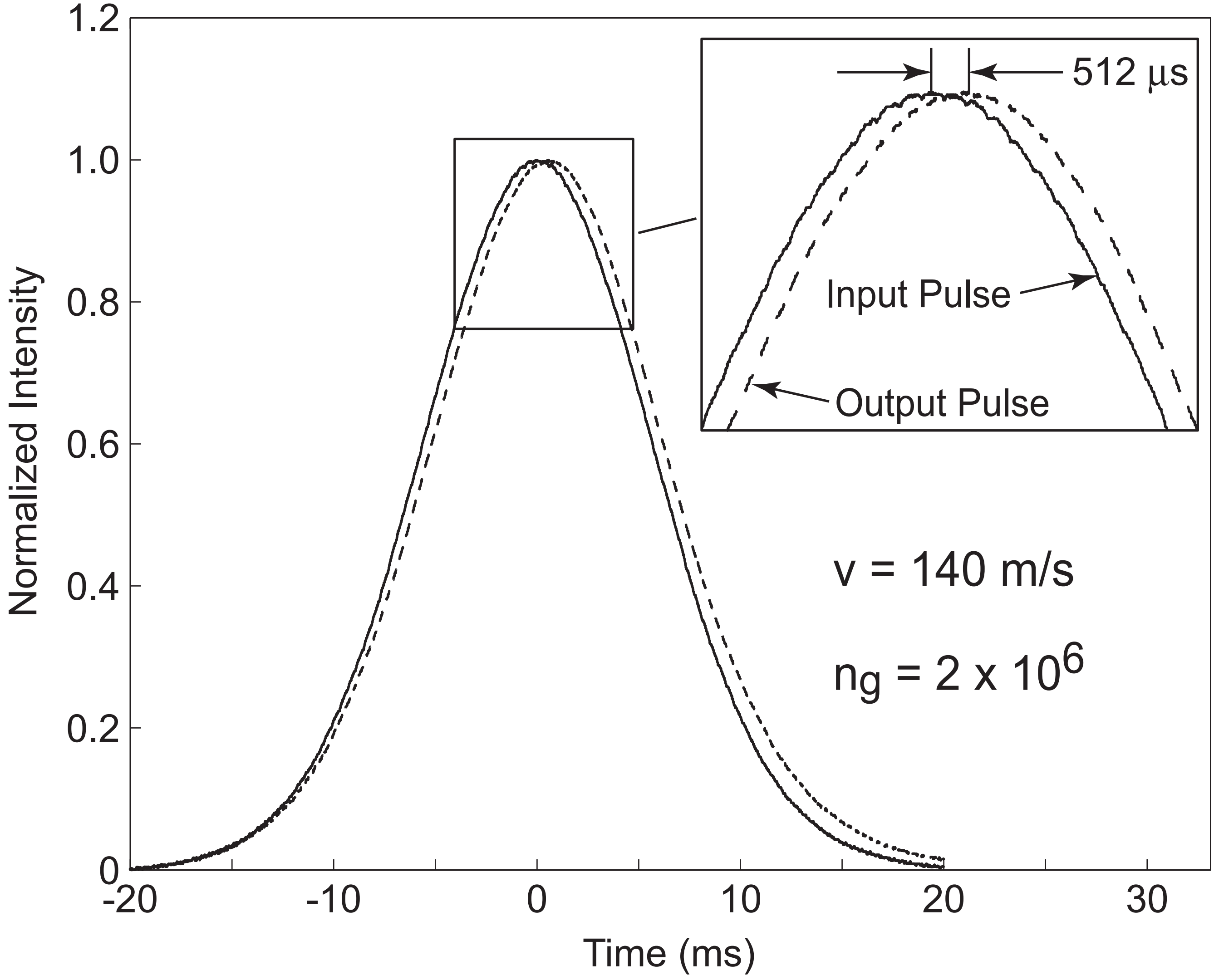
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



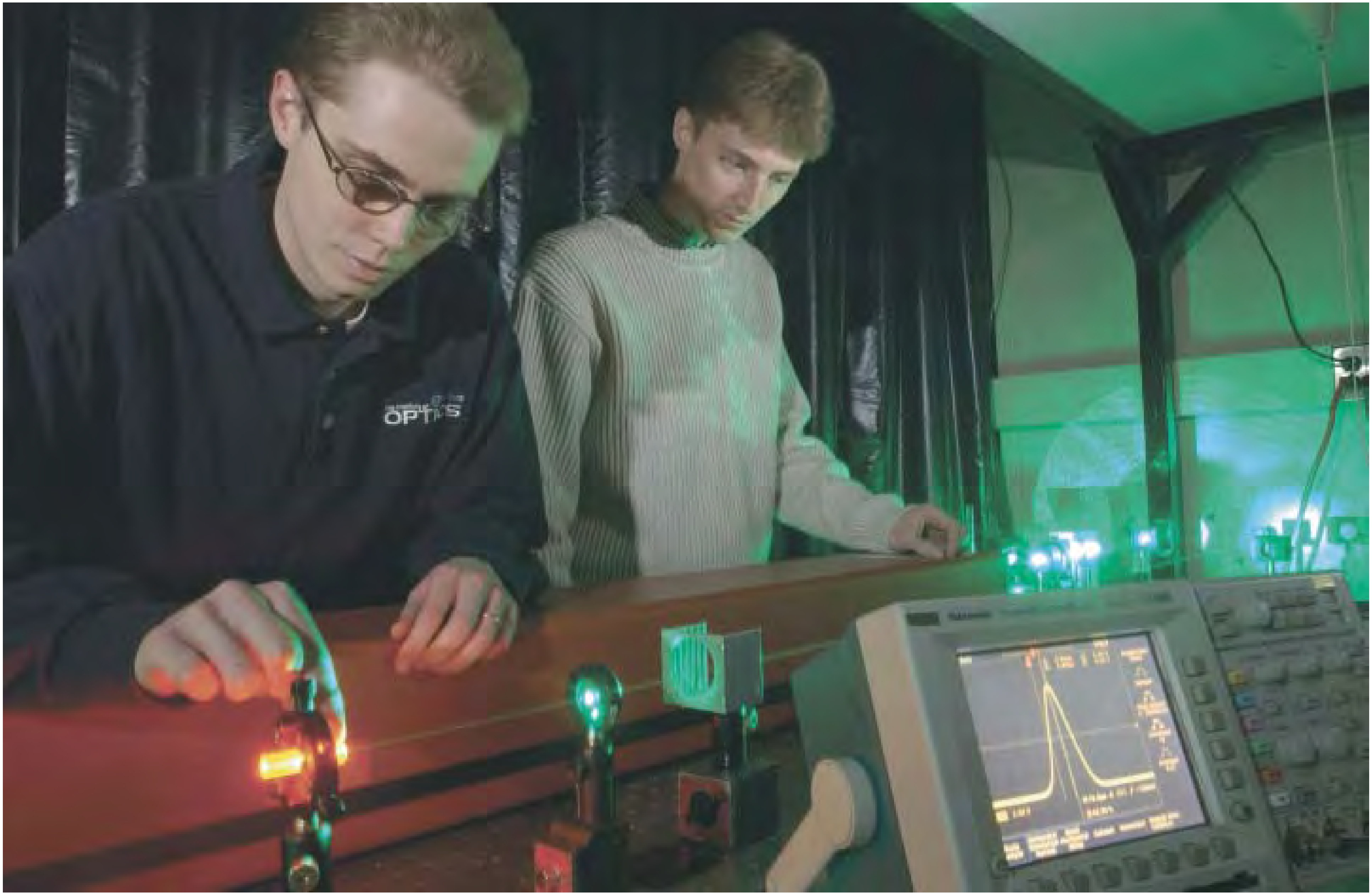
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

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

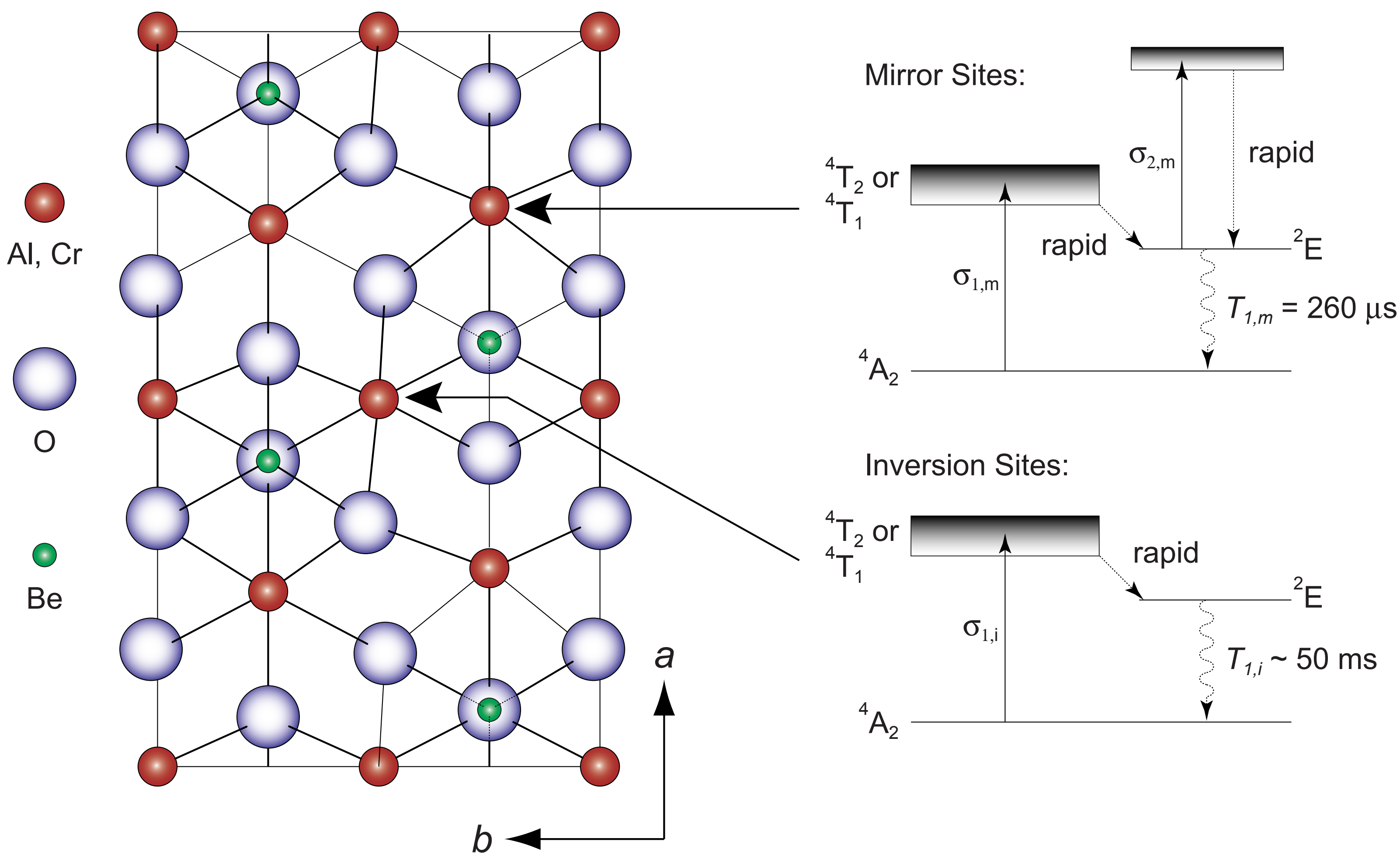
Laser need not be frequency stabilized

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

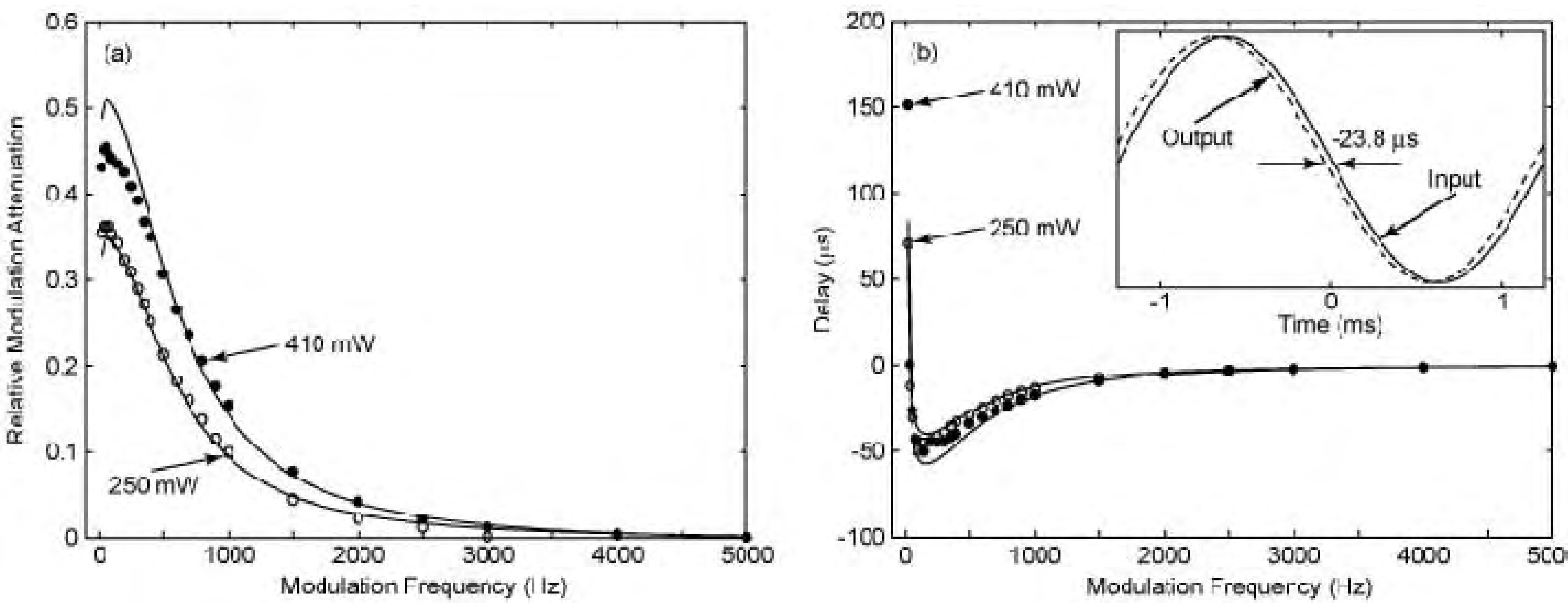


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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.

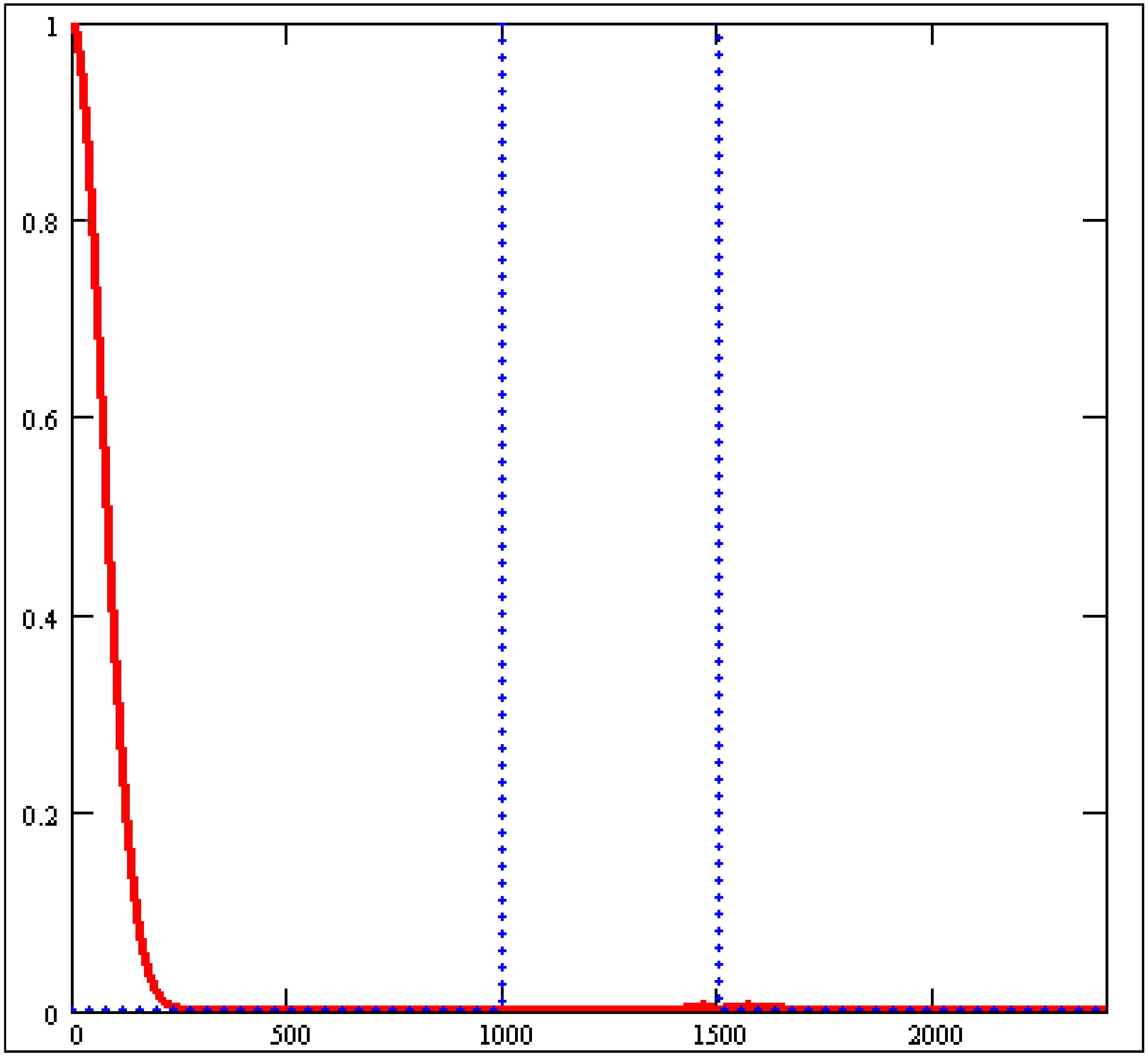
Study three cases:

Slow light $v_g = 0.5\ c$

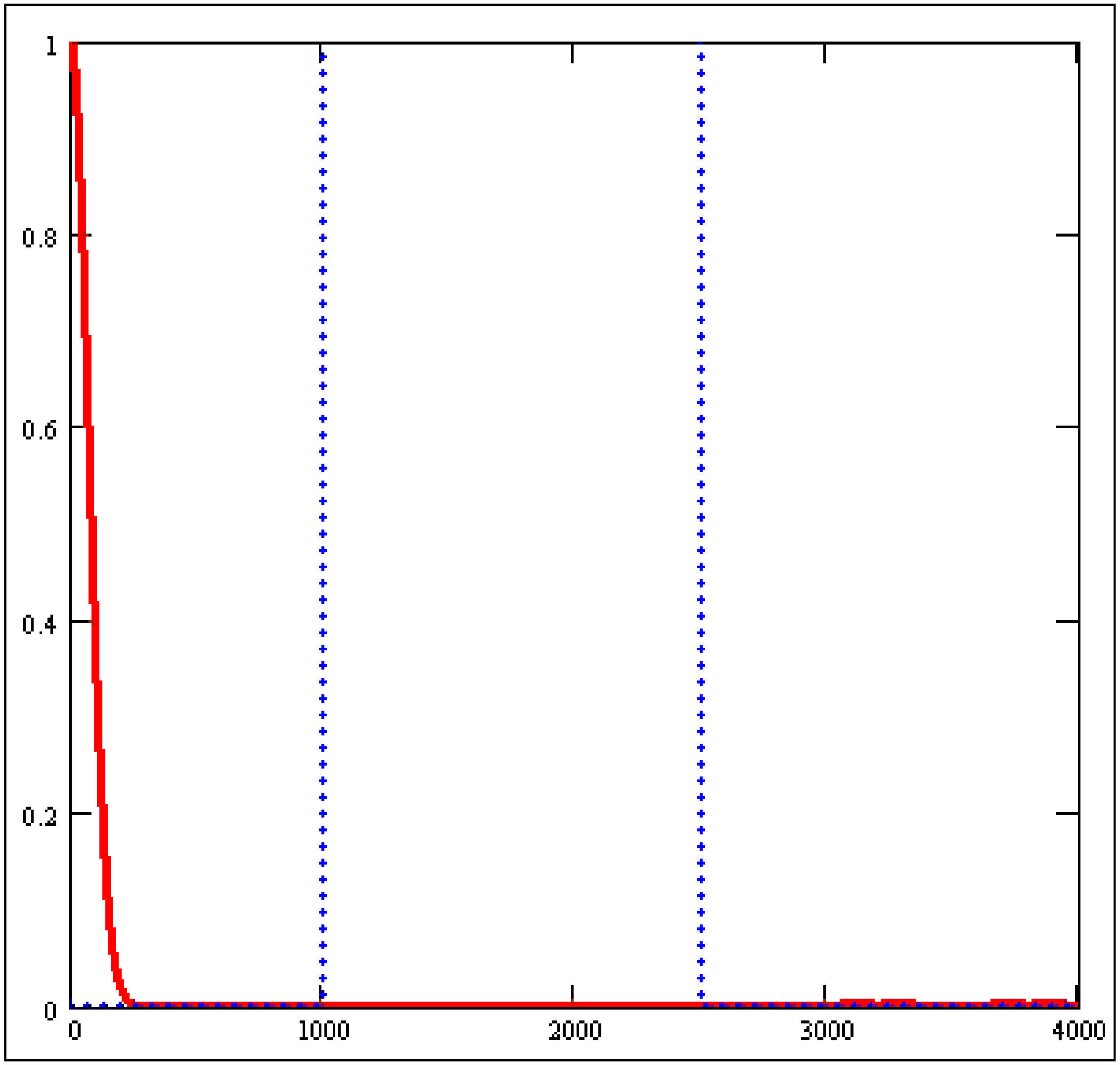
Fast light $v_g = 5\ c$ and $v_g = -2\ c$

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

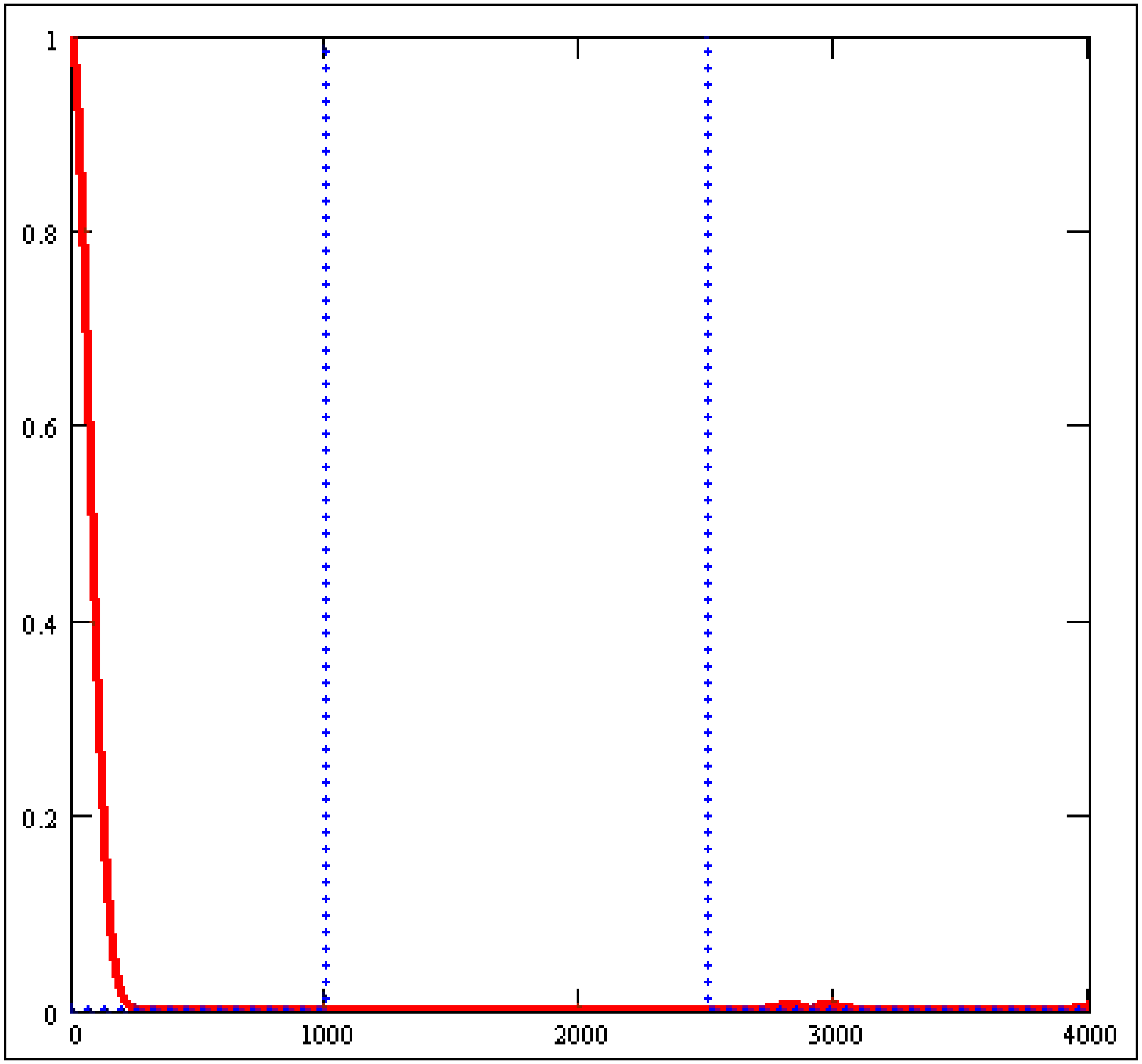
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



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

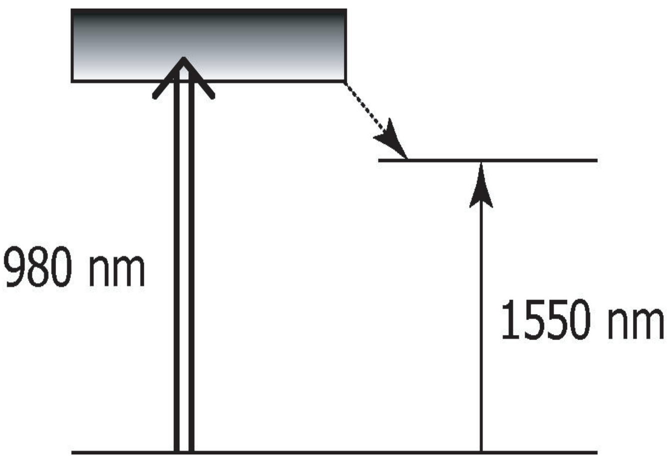


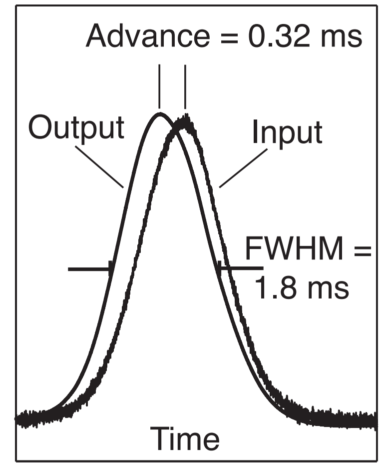
Pulse Propagation through a Fast-Light Medium (n_g = -.5, v_g = -2 c)

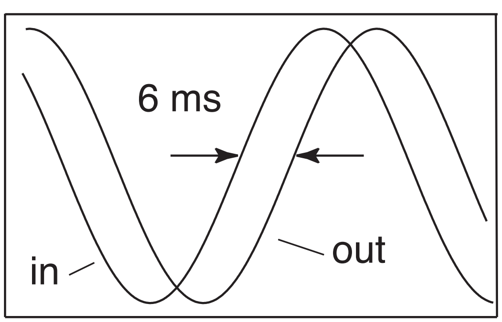


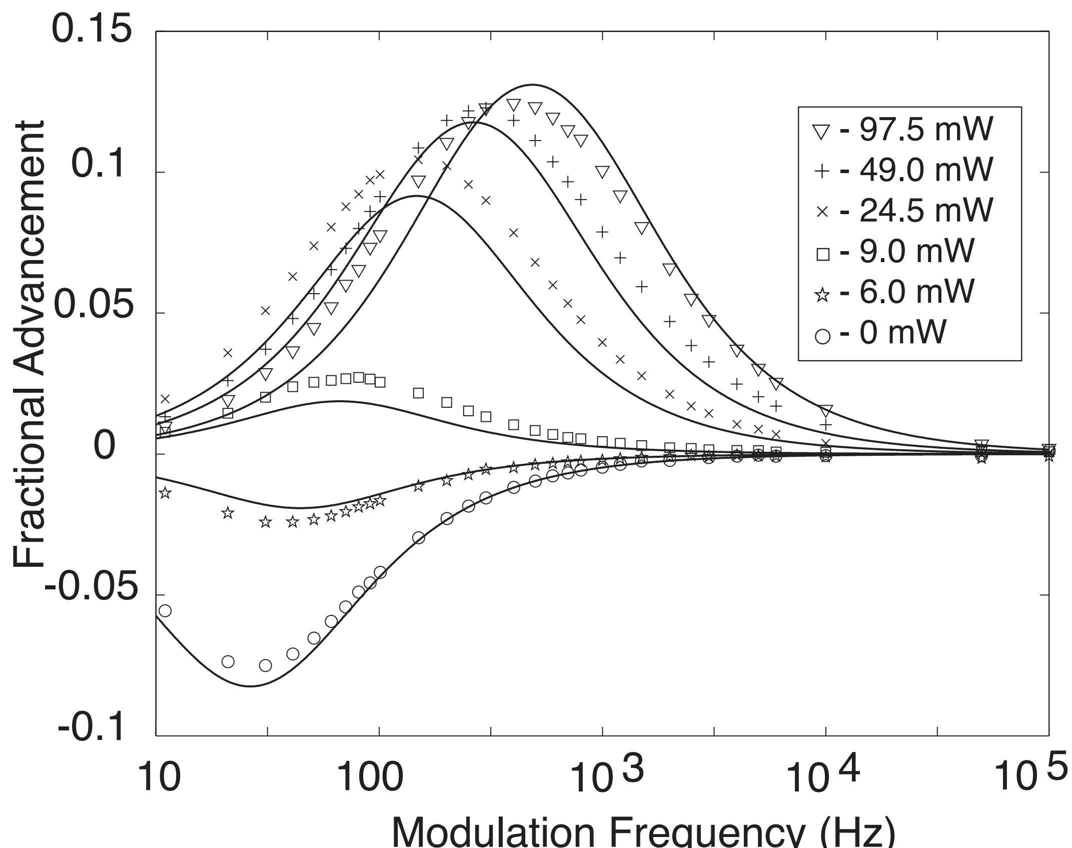
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



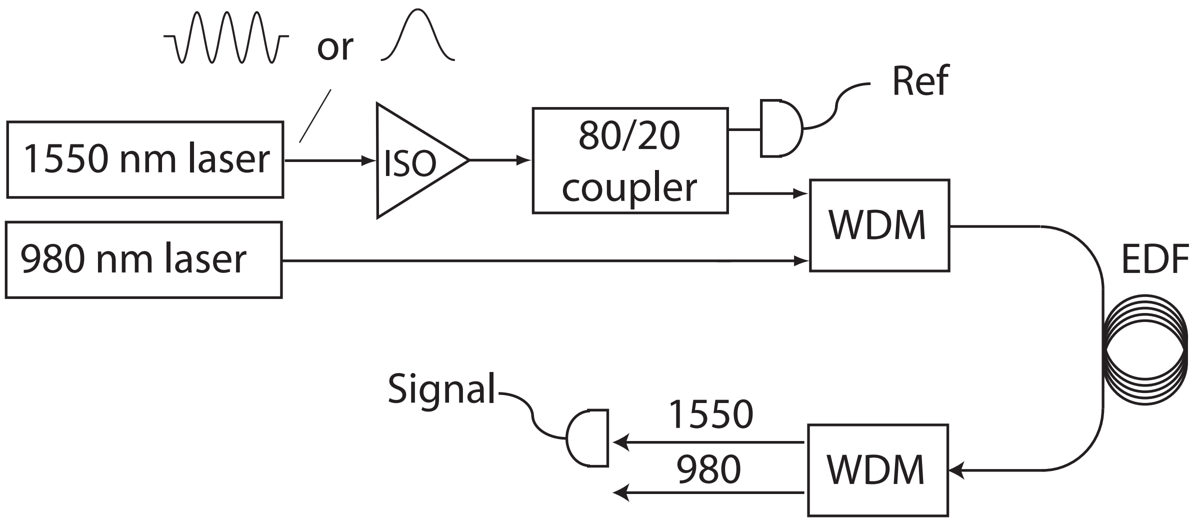






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

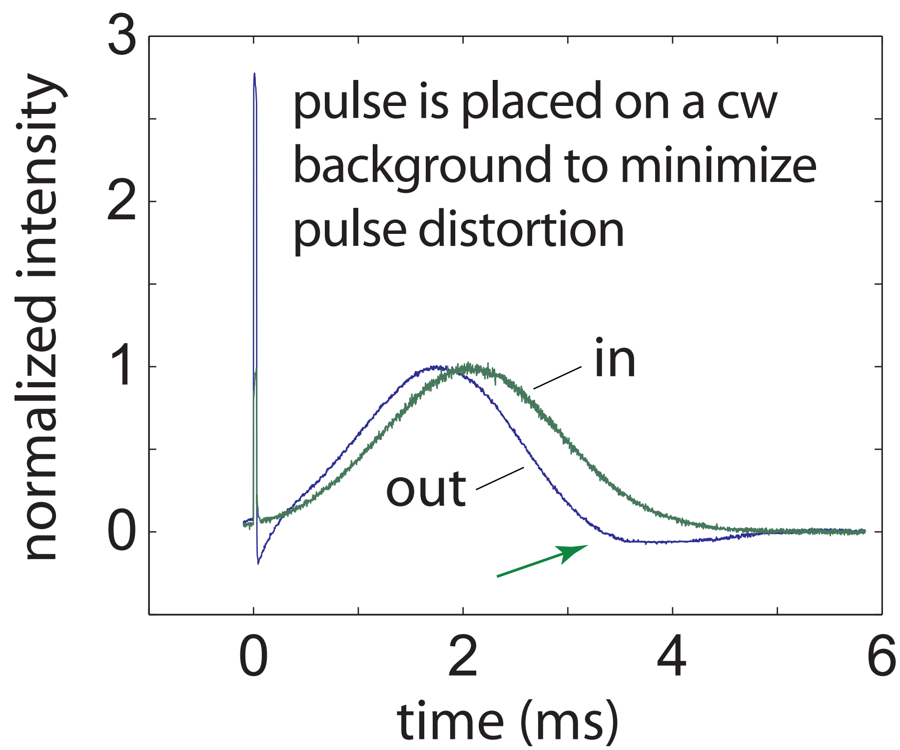
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



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

Procedure

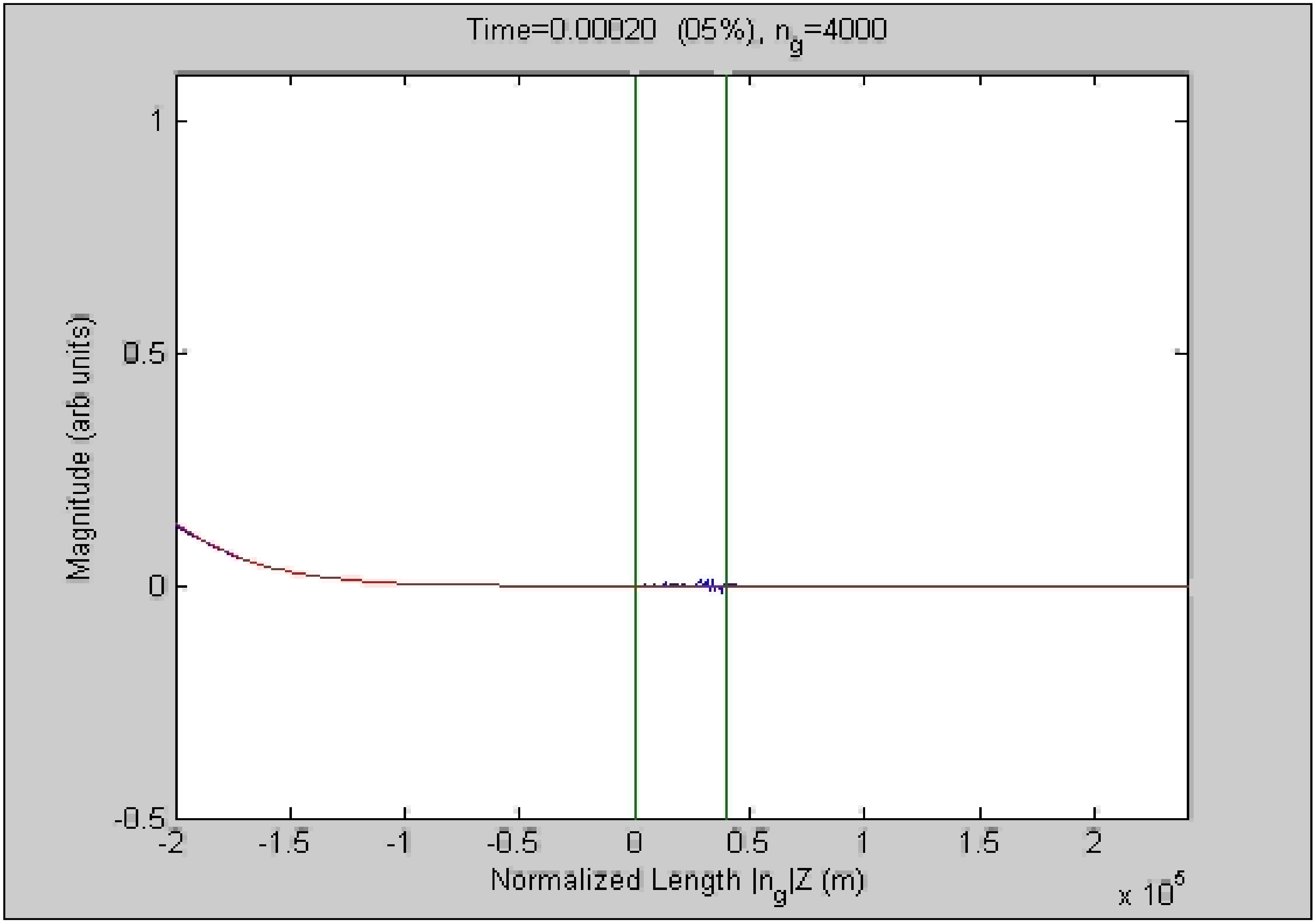
- cutback method
- couplers embedded in fiber



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

Experimental Results: Backward Propagation in Erbium-Doped Fiber

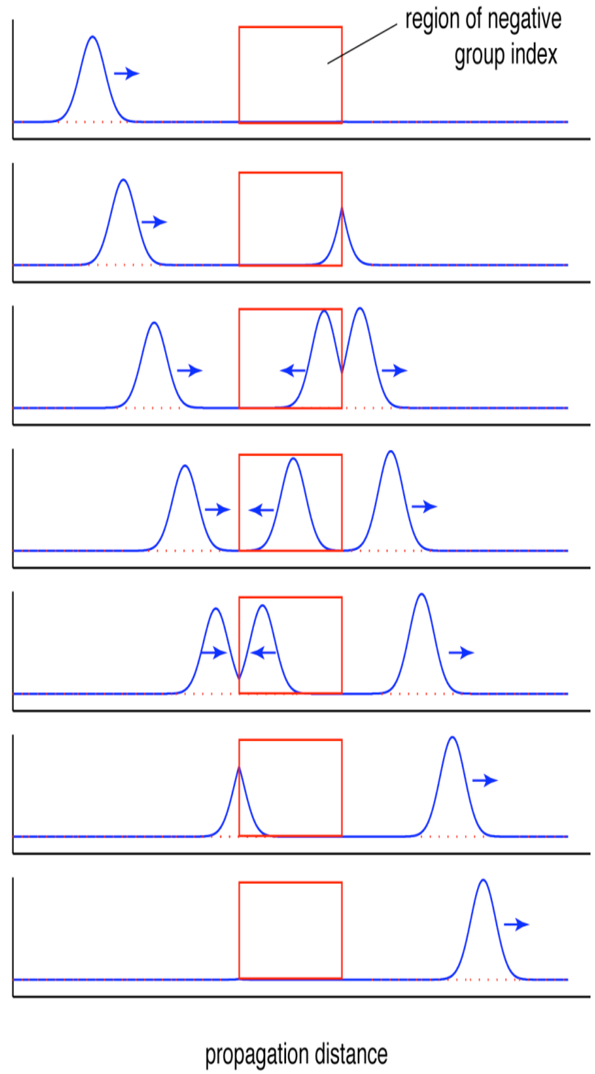
Normalized: (Amplification removed numerically)



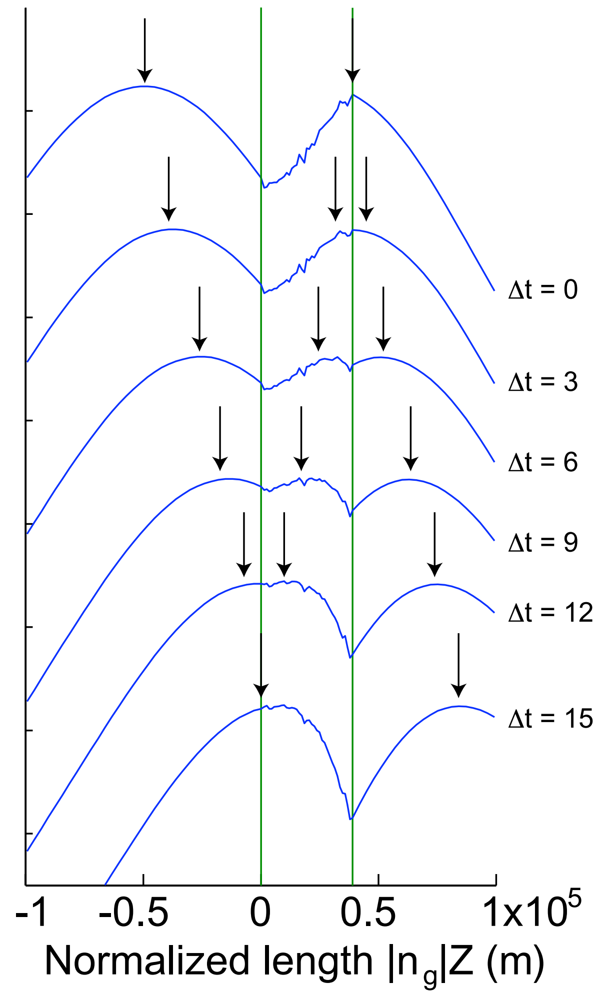
Observation of "Backwards" Pulse Propagation

- 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

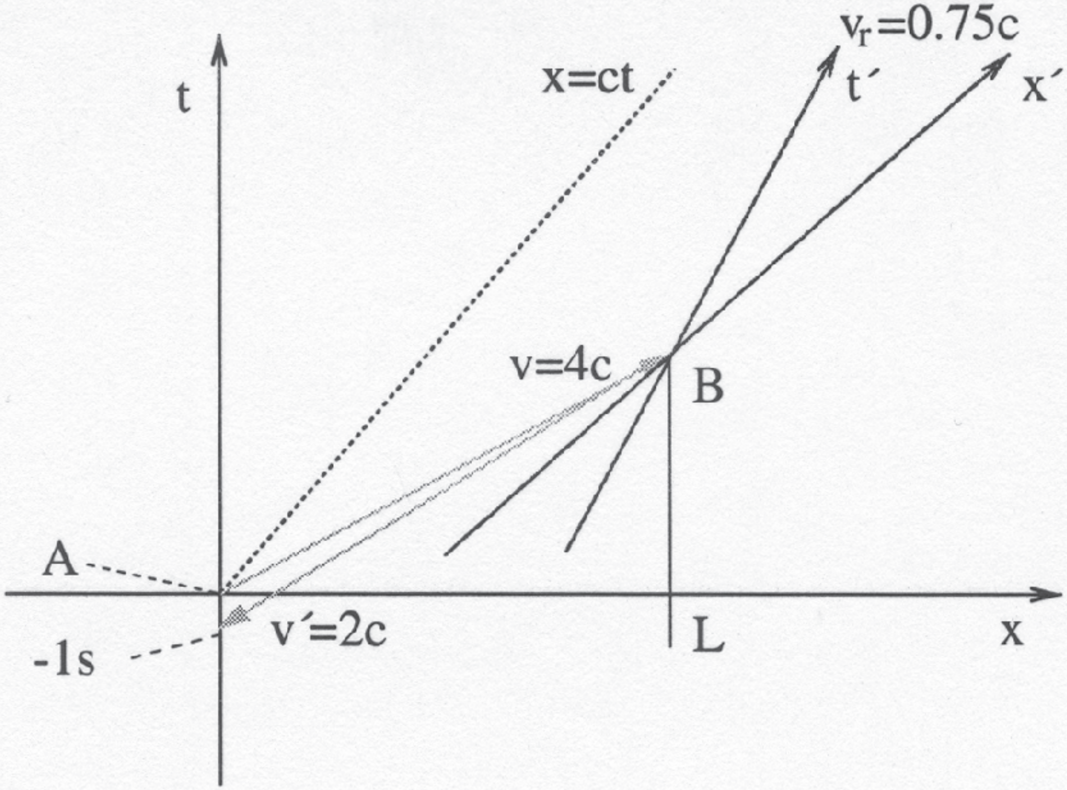
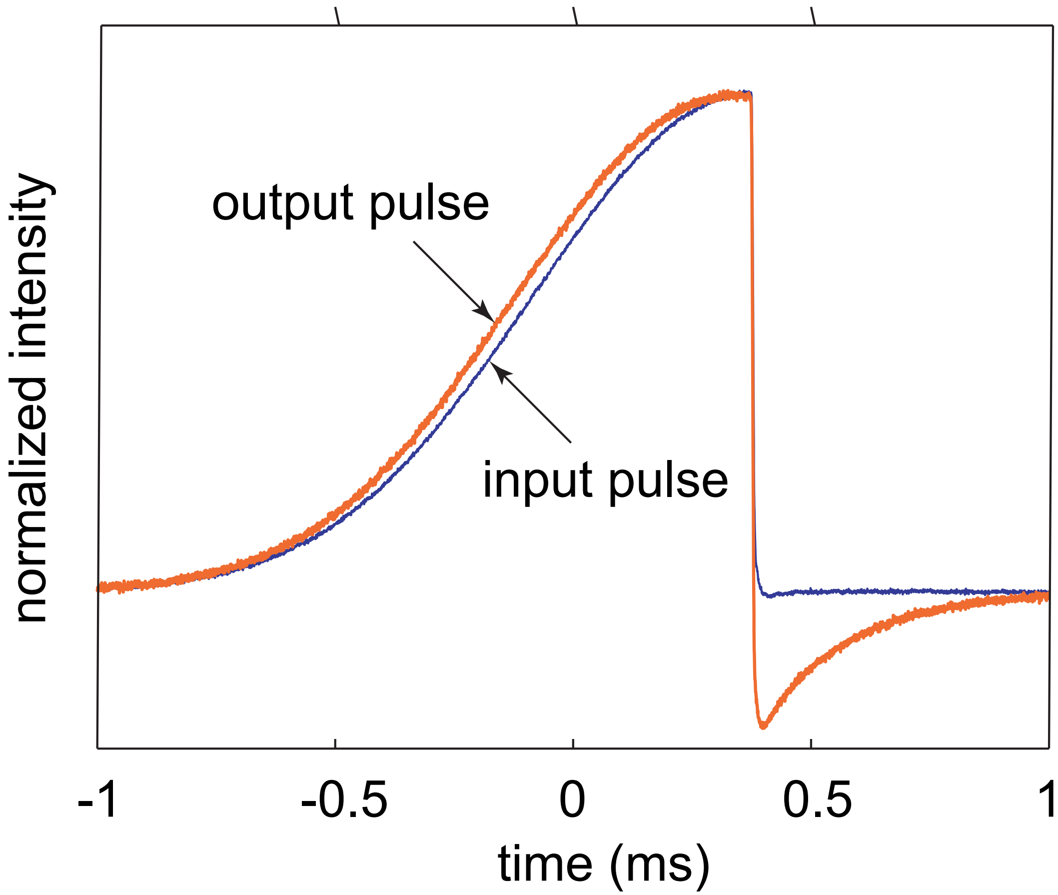


Fig. 6 Coordinates of two inertial observers **A** $(0,0)$ and **B** with $O(x,t)$ and $O'(x',t')$ moving with a relative velocity of $0.75c$. The distance L between **A** and **B** is 2 000 000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v_s' = 2c$. The numbers in the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

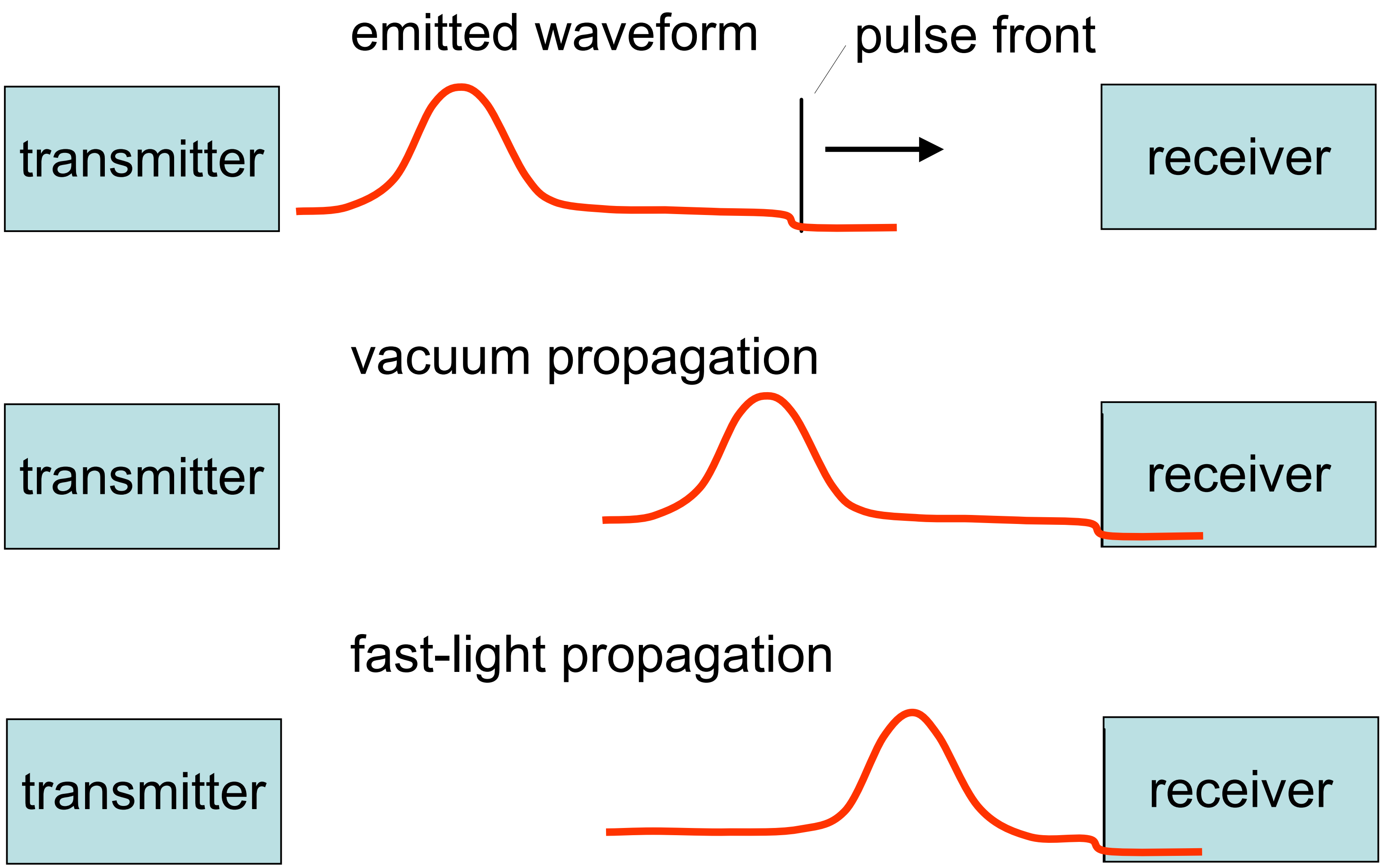
Discontinuity propagates at phase velocity

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.

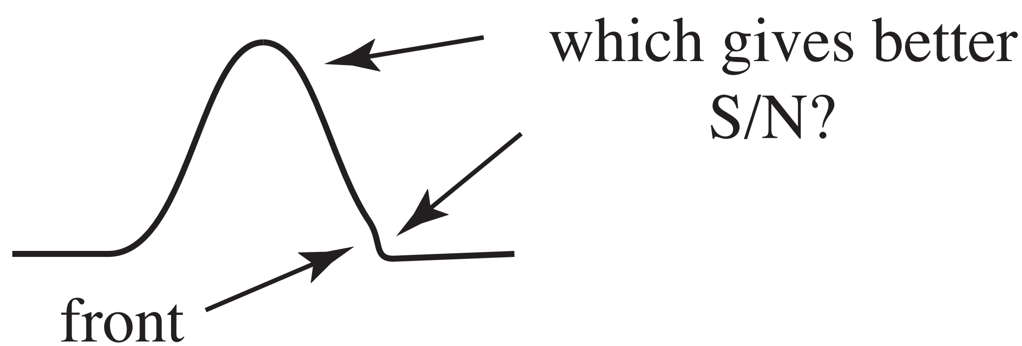
Information Velocity – Tentative Conclusions

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.

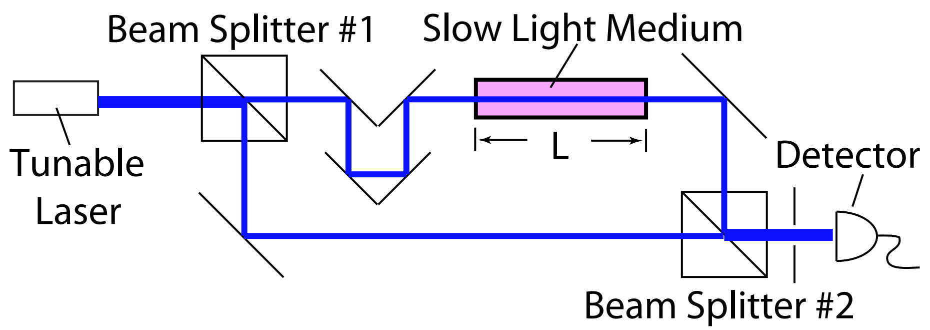


Brief Research Update

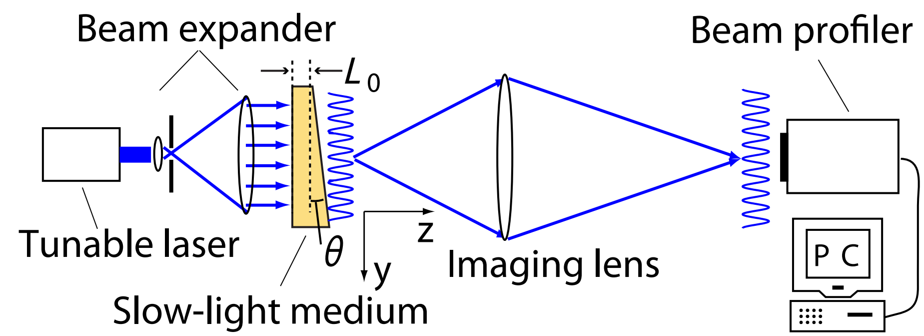
Interferometry and Slow Light

- 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

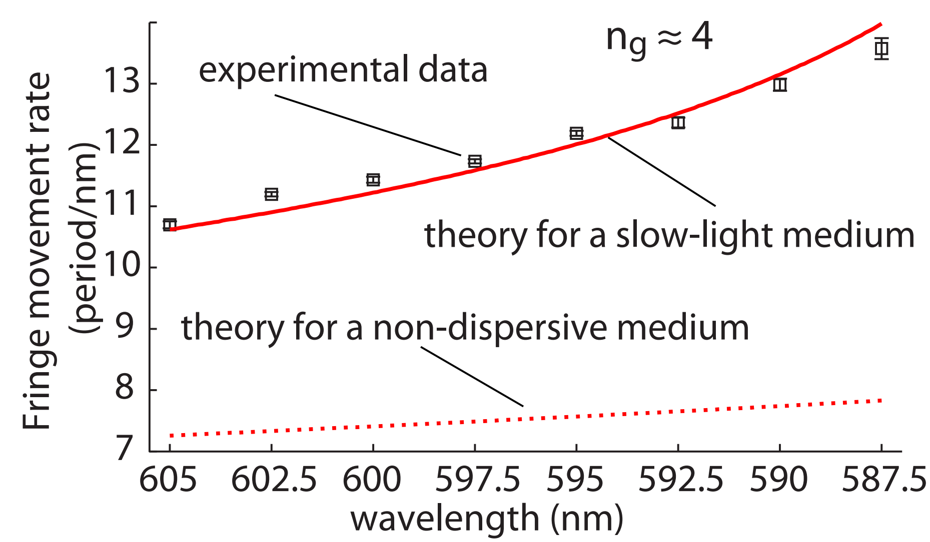


Here is why it works:

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

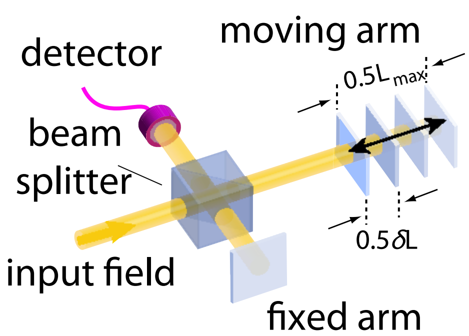
Shih et al, Opt. Lett. 2007

Our experimental results

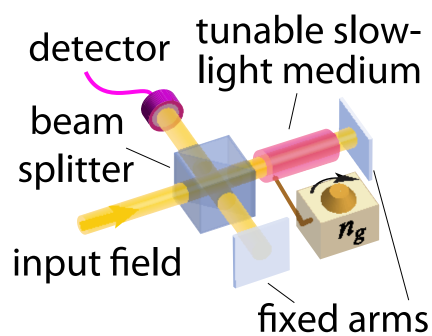


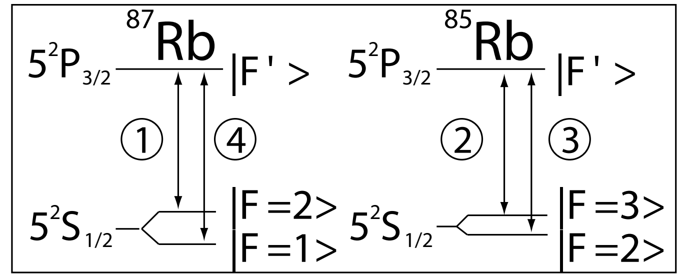
High-Resolution Slow-Light Fourier Transform Interferometer

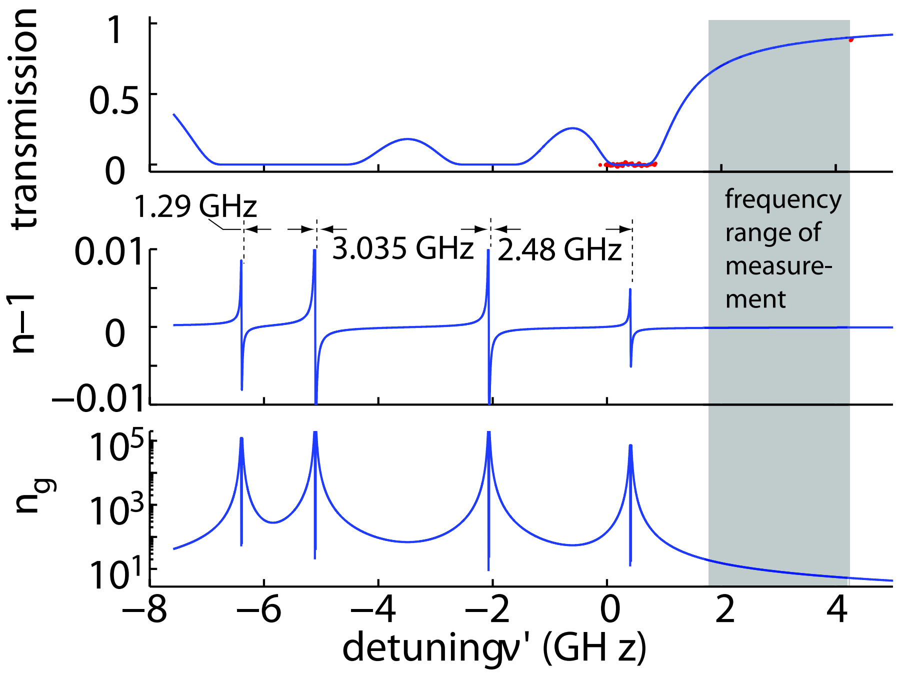
conventional FT Interferometer

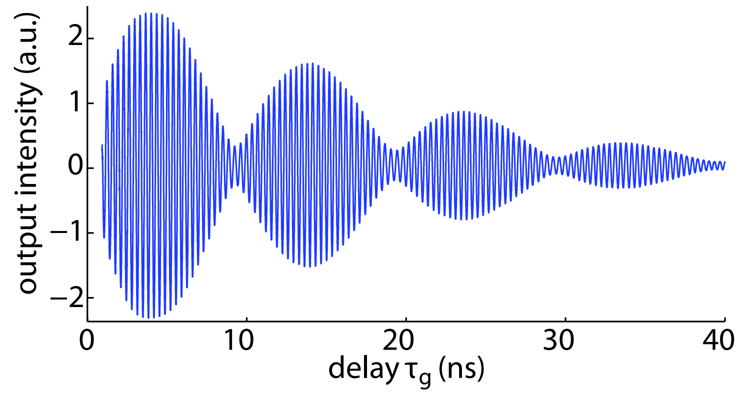


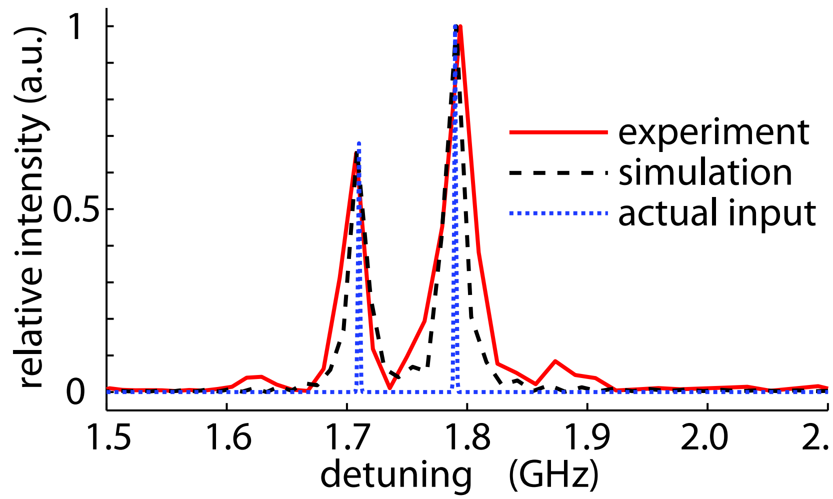
slow-light FT Interferometer







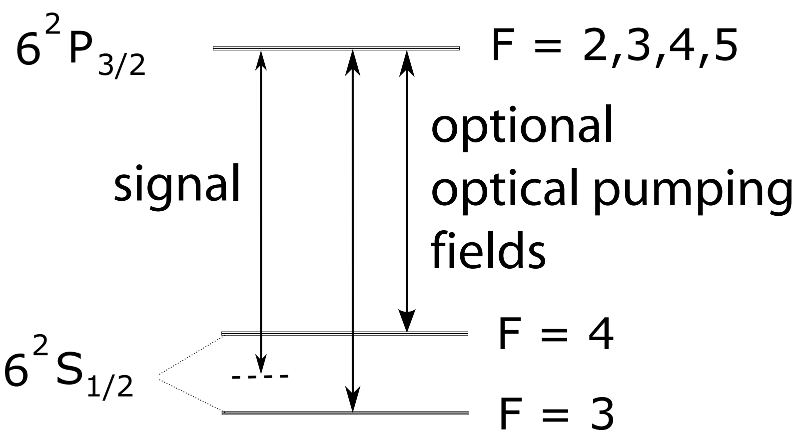




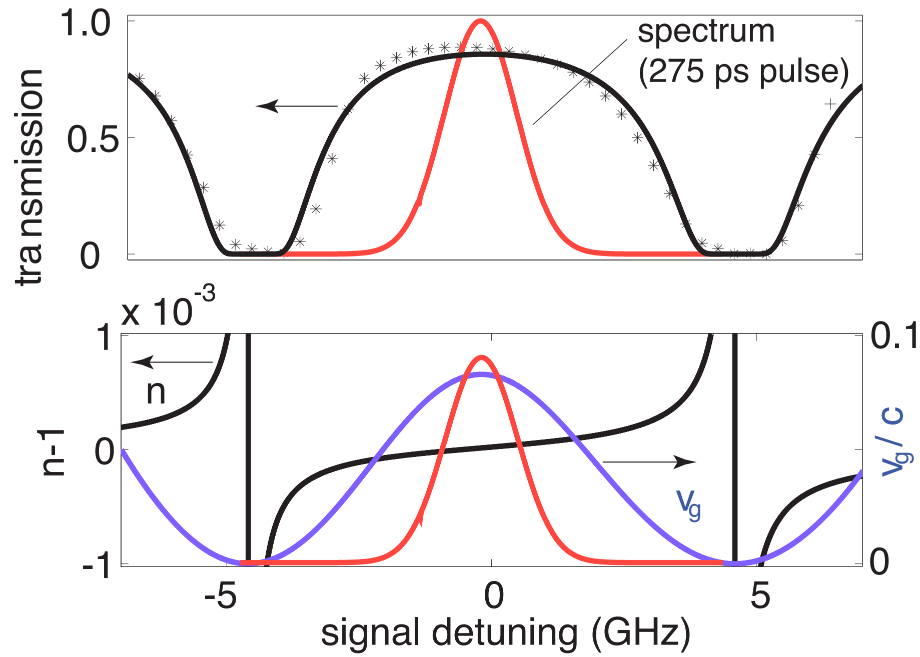
Shi, Boyd, Camacho, Setu, and Howell

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

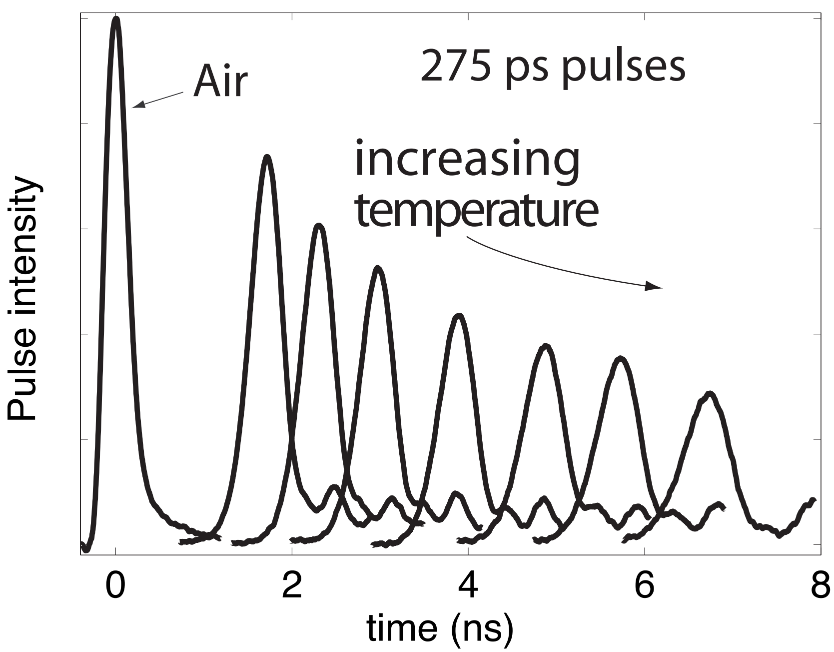
There is no delay-bandwidth product limitation on slow light!



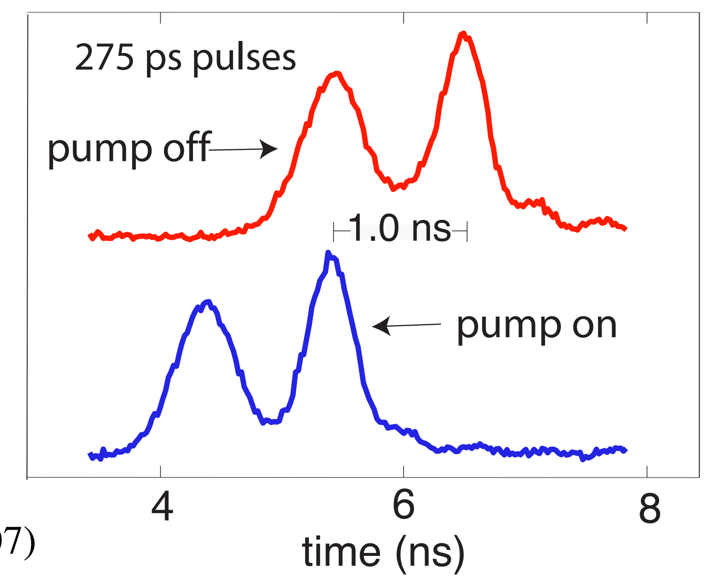
group index approximately 10 to 100



- coarse tuning: temperature



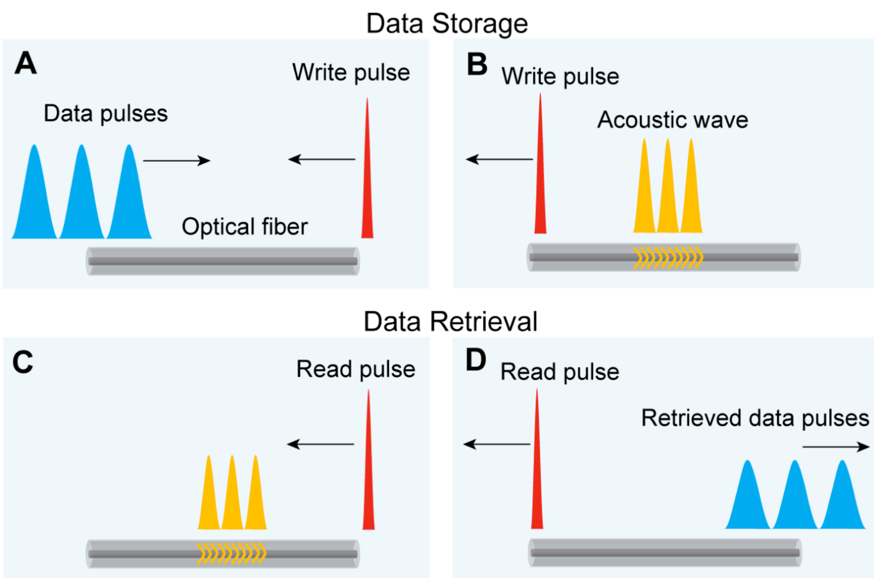
- fine tuning: optical pumping



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

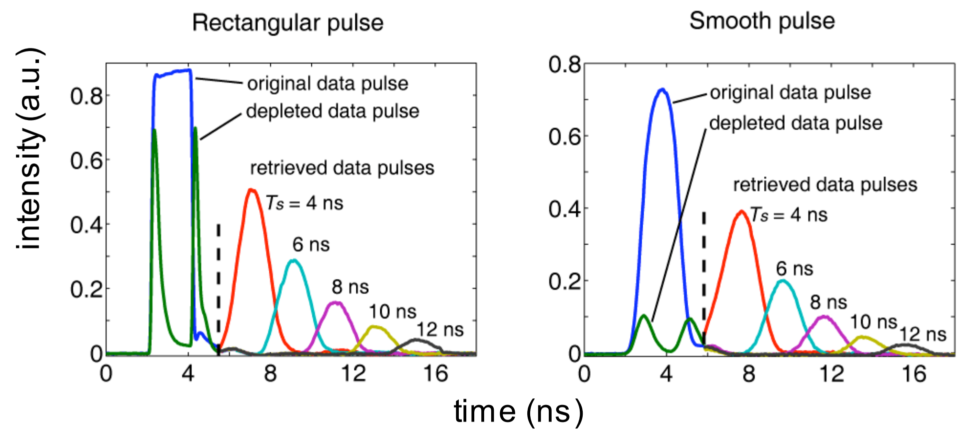
Stored Light via SBS *(Duke/Rochester effort)*

The Concept: Covert information encoded on an optical wave into an acoustic wave via stimulated Brillouin scattering. A read out pulse converts the acoustic wave back to the optical domain.

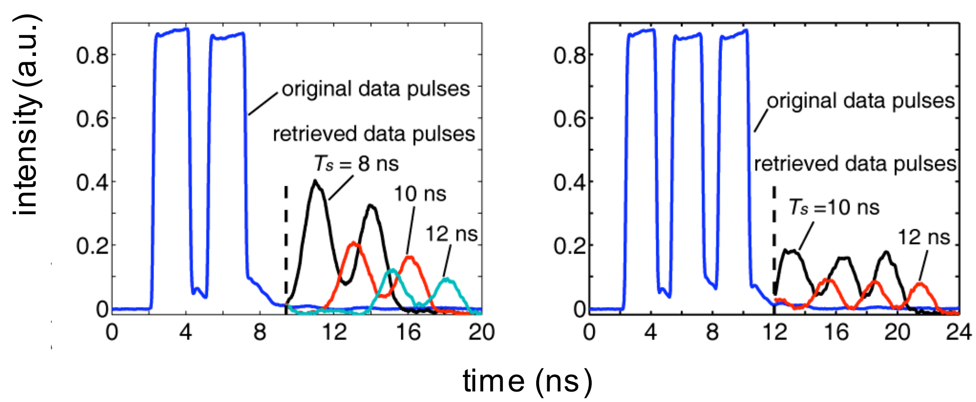


Experimental Results

single-pulse storage and retrieval

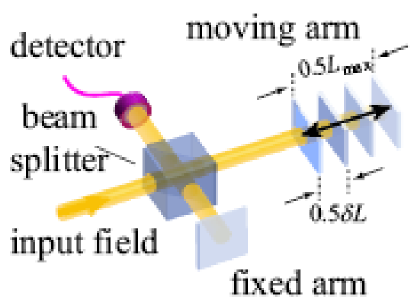


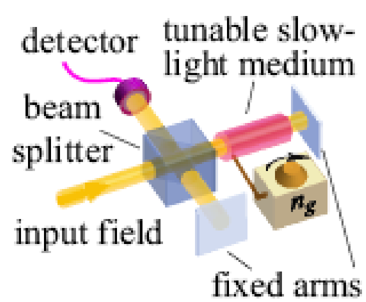
multiple-pulse storage and retrieval

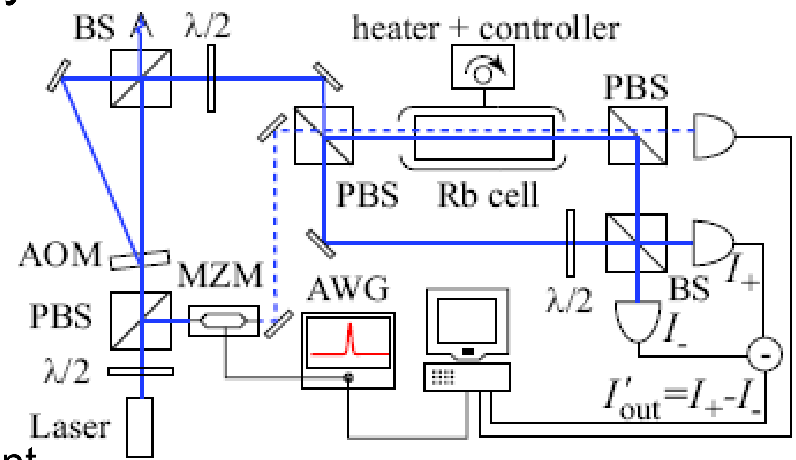


Phase II milestone for stored light via SBS is essentially achieved

I. Slow Light Fourier Transform Interferometry

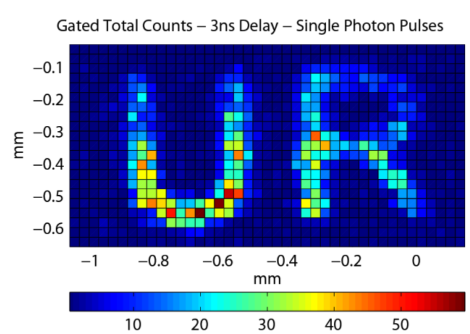


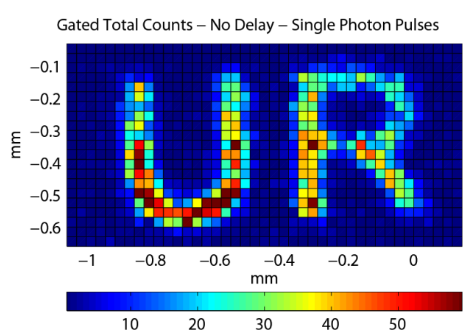


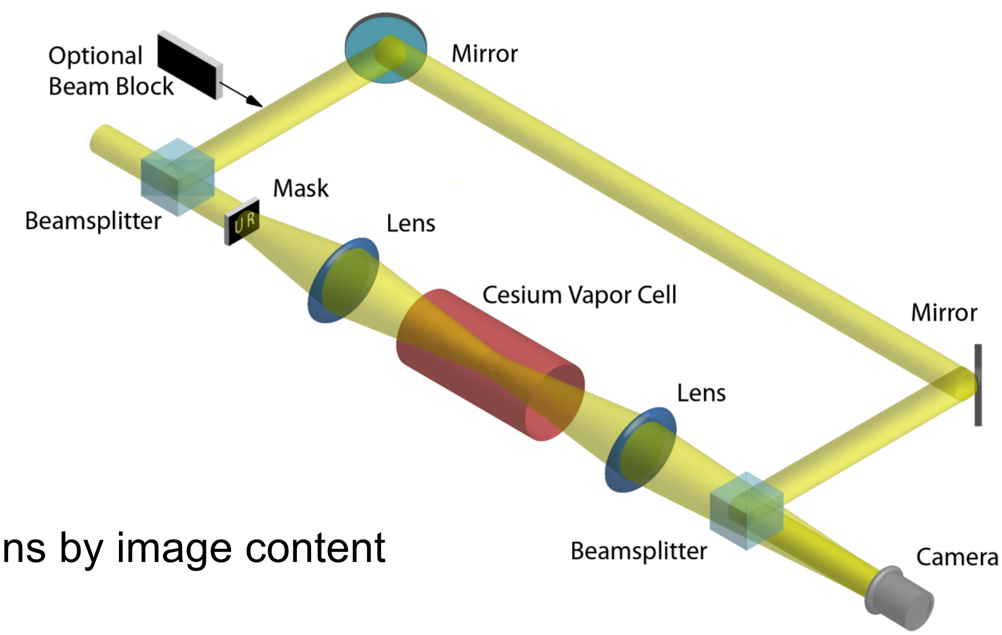


We have now achieved a 100X resolution enhancement

II. Imaging Through a Slow-Light Medium







Currently working on sorting of individual photons by image content

Slow Light in Optical Fibers: Applications of Slow Light in Telecom

Robert W. Boyd

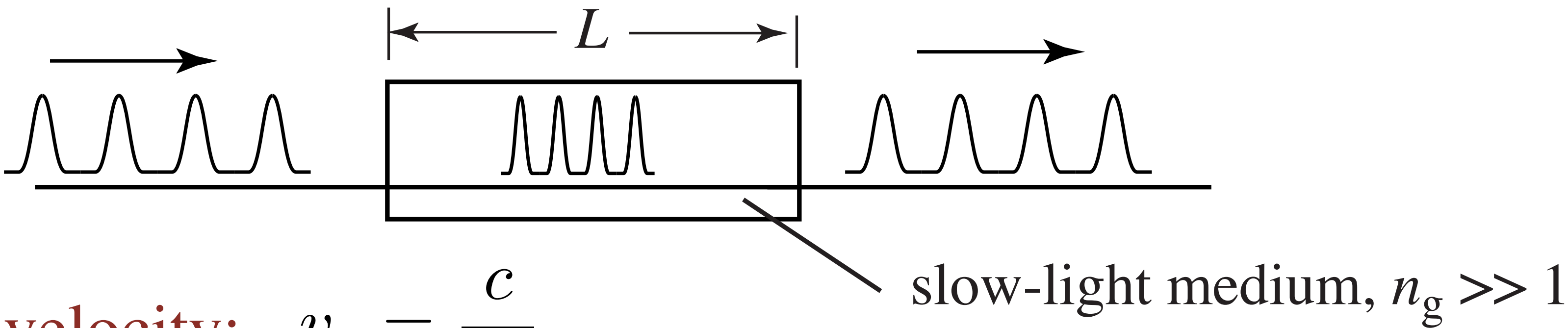
Institute of Optics and
Department of Physics and Astronomy
University of Rochester

with Aaron Schweinsberg, Petros Zerom, Giovanni Piredda,
Zhimin Shi, Heedeuk Shin, and others

Slow Light in Optical Fibers: Applications of Slow Light in Telecom

1. Introduction, motivation, our research team
2. Modeling of slow light systems: maximum time delay
3. Progress in laboratory implementation of slow light methods
4. Physics of slow-light interactions, causality issues
5. Summary and conclusions

Review of Slow-Light Fundamentals



group velocity: $v_g = \dfrac{c}{n_g}$

group index: $n_g = n + \omega \dfrac{dn}{d\omega}$

group delay: $T_g = \dfrac{L}{v_g} = \dfrac{L n_g}{c}$

controllable delay: $T_{\mathrm{del}} = T_g - L/c = \dfrac{L}{c}(n_g - 1)$

To make controllable delay as large as possible:

- make *L* as large as possible (reduce residual absorption)
- maximize the group index

Systems Considerations: Maximum Slow-Light Time Delay

"Slow light": group velocities < 10^{-6} c !

Proposed applications: controllable optical delay lines
optical buffers, true time delay for synthetic aperture radar.

Key figure of merit:
normalized time delay = total time delay / input pulse duration
≈ information storage capacity of medium

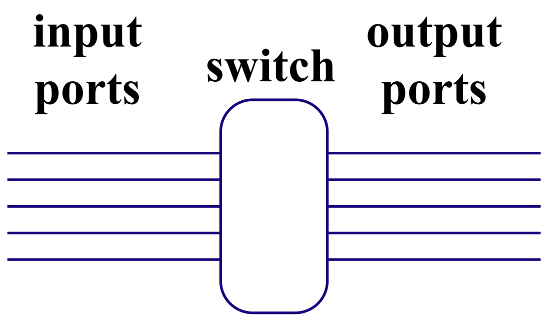
Best result to date: delay by 4 pulse lengths (Kasapi et al. 1995)

But data packets used in telecommunications contain ≈ 10^3 bits

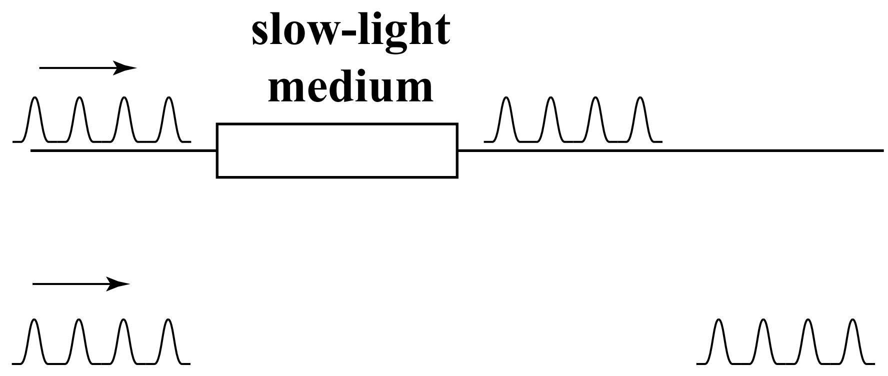
What are the prospects for obtaining slow-light delay lines with 10^3 bits capacity?

Slow Light and Optical Buffers

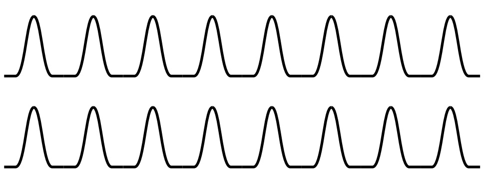
All-Optical Switch



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

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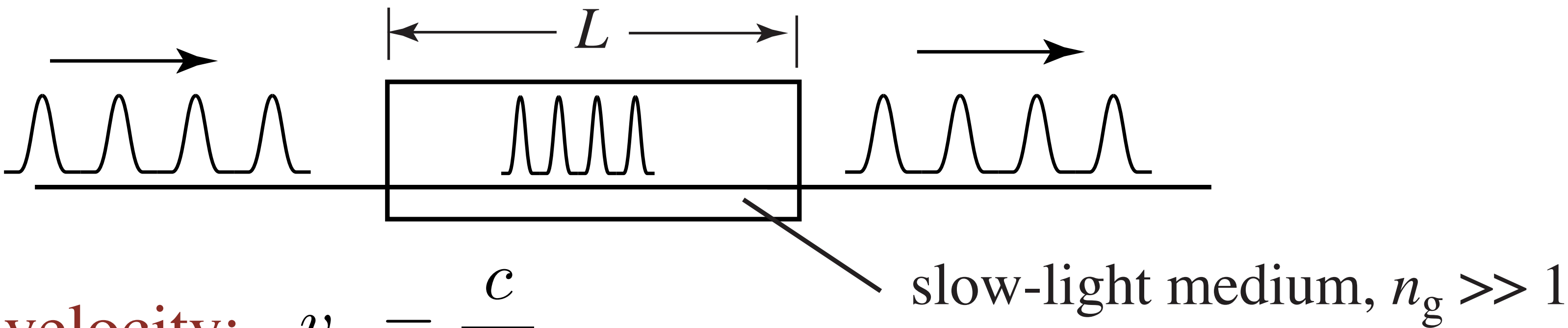

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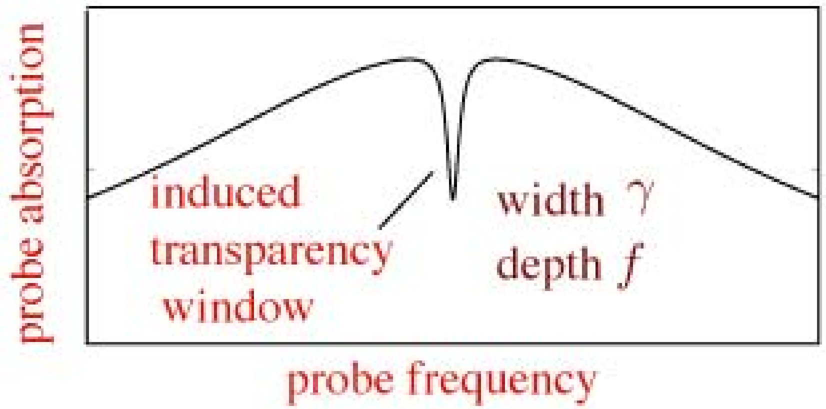
To make controllable delay as large as possible:

- make *L* as large as possible (reduce residual absorption)
- maximize the group index

Generic Model of EIT and CPO Slow-Light Systems



probe absorption

$$\alpha(\delta) = \alpha_0 \left(1 - \frac{f}{1+\delta^2/\gamma^2}\right) \approx \alpha_0 \left[(1-f) - f\frac{\delta^2}{\gamma^2}\right] \quad \text{where} \quad \delta = \omega - \omega_0$$

probe refractive index (by Kramers Kronig)

$$n(\delta) = n_0 + f\left(\frac{\alpha_0 \lambda}{4\pi}\right)\frac{\delta/\gamma}{1+\delta^2/\gamma^2} \approx n_0 + f\left(\frac{\alpha_0 \lambda}{4\pi}\right)\frac{\delta}{\gamma}\left(1 - \frac{\delta^2}{\gamma^2}\right)$$

probe group index

$$n_g \approx f\left(\frac{\alpha_0 \lambda}{4\pi}\right)\frac{\omega}{\gamma}\left(1 - \frac{3\delta^2}{\gamma^2}\right).$$

induced delay

$$T_{\mathrm{del}} \approx \frac{f\alpha_0 L}{2\gamma}\left(1 - \frac{3\delta^2}{\gamma^2}\right)$$

normalized induced delay (T_0 = pulse width)

$$\frac{T_{\mathrm{del}}}{T_0} \approx \frac{f\alpha_0 L}{2\gamma T_0}\left(1 - \frac{3\delta^2}{\gamma^2}\right)$$

Limitations to Time Delay

Normalized induced delay

$$\frac{T_{\mathrm{del}}}{T_0} \approx \frac{f\alpha_0 L}{2\gamma T_0}\left(1 - \frac{3\delta^2}{\gamma^2}\right)$$

Limitation 1: Residual absorption limits L; Solution: Eliminate residual absorption

Limitation 2: Group velocity dispersion

A short pulse will have a broad spectrum and thus a range of values of δ
There will thus be a range of time delays, leading to a range of delays and pulse spreading
Insist that pulse not spread by more than a factor of 2. Thus

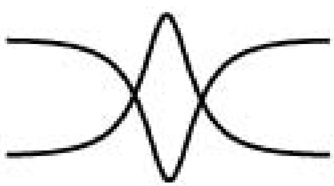
$$L_{\max} = 2\gamma^3 T_0^3 / 3f\alpha_0 \qquad \text{and} \qquad \left(\frac{T_{\mathrm{del}}}{T_0}\right)_{\max} = \frac{1}{3}\gamma^2 T_0^2.$$

Limitation 3: Spectral reshaping of pulse (more restrictive than limitation 2)

Pulse will narrow in frequency and spread in time
from T_0 to T where $T^2 = T_0^2 + f\alpha_0 L/\gamma^2$.

Thus

$$L_{\max} = 3T_0^2\gamma^2/(2f\alpha_0) \quad \text{and} \quad \left(\frac{T_{\mathrm{del}}}{T_0}\right)_{\max} = \frac{3}{2}\gamma T_0.$$



Note that γT_0 can be arbitrarily large!

Summary: Fundamental Limitations to Time Delay

- If one can eliminate residual absorption, the maximum relative time delay is

$$\left(\frac{T_{\mathrm{del}}}{T_0}\right)_{\mathrm{max}} = \frac{3}{2}\gamma T_0,$$

which has no upper bound.

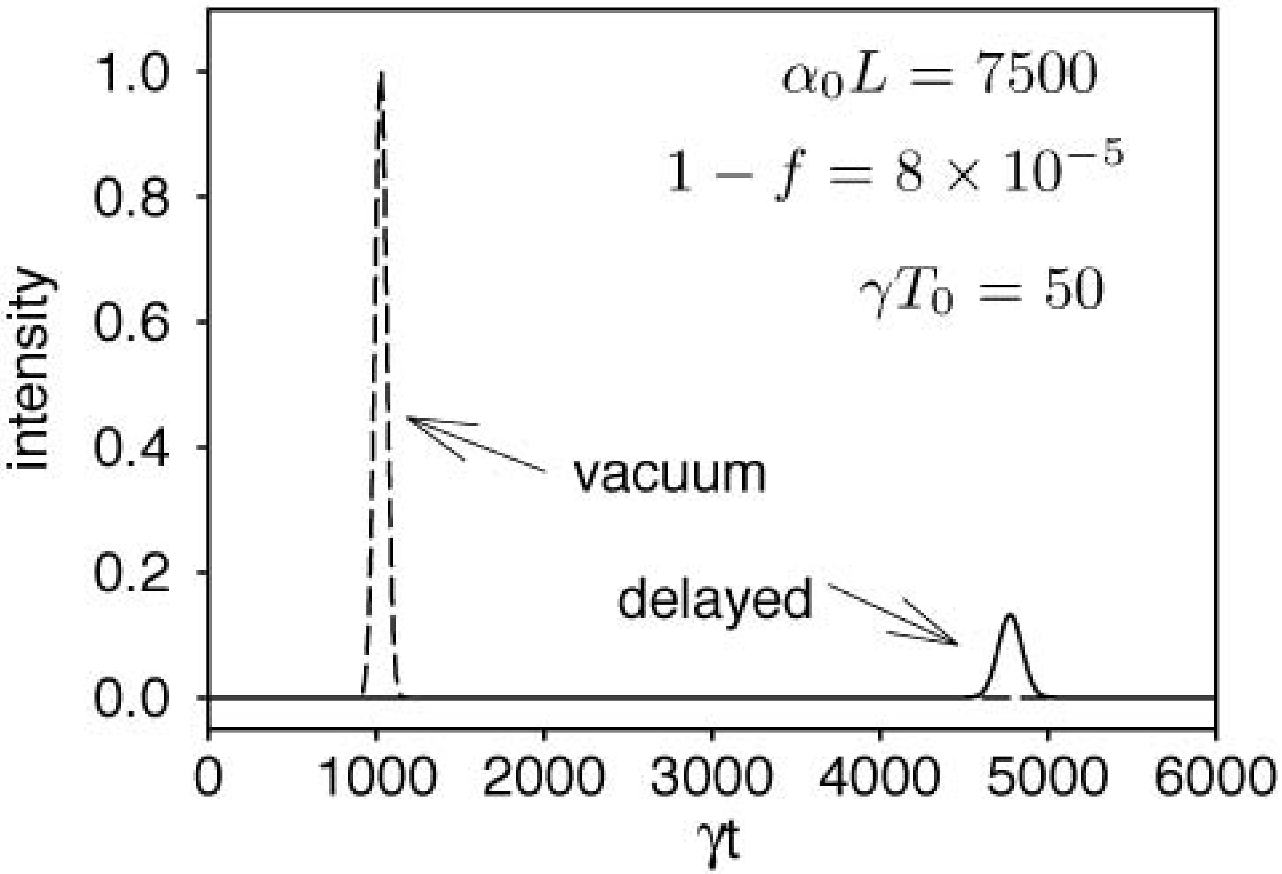
- But to achieve this time delay, one needs a large initial (before saturation) optical depth given by

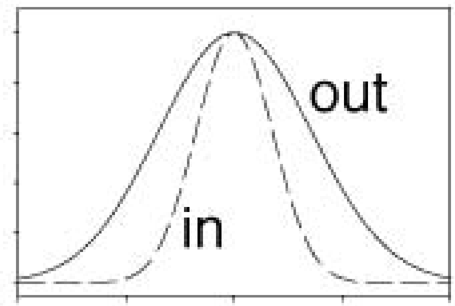
$$\alpha_0 L = (4/3)(T_{\mathrm{del}}/T_0)^2_{\mathrm{max}}.$$

- For typical telecommunications protocols, the bit rate B is approximately T_0^{-1} and the required transparency linewidth must exceed the bit rate by the relative delay

$$\gamma = \frac{2}{3} B \left(\frac{T_{\mathrm{del}}}{T_0}\right)_{\mathrm{max}}$$

Numerical Example Showing Large Relative Delay





Factor-of-two pulse spreading

Relative time delay $T_{\mathrm{del}}/T_0 = 75$.

Modeling of Slow-Light Systems

We conclude that there are no *fundamental* limitations to the maximum fractional pulse delay [1]. Our model includes gvd and spectral reshaping of pulses.

However, there are serious *practical* limitations, primarily associated with residual absorption.

Another recent study [2] reaches a more pessimistic (although entirely mathematically consistent) conclusion by stressing the severity of residual absorption, especially in the presence of Doppler broadening.

Our challenge is to minimize residual absorption.

[1] Boyd, Gauthier, Gaeta, and Willner, Phys. Rev. A 71, 023801, 2005.

[2] Matsko, Strekalov, and Maleki, Opt. Express 13, 2210, 2005.

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?**

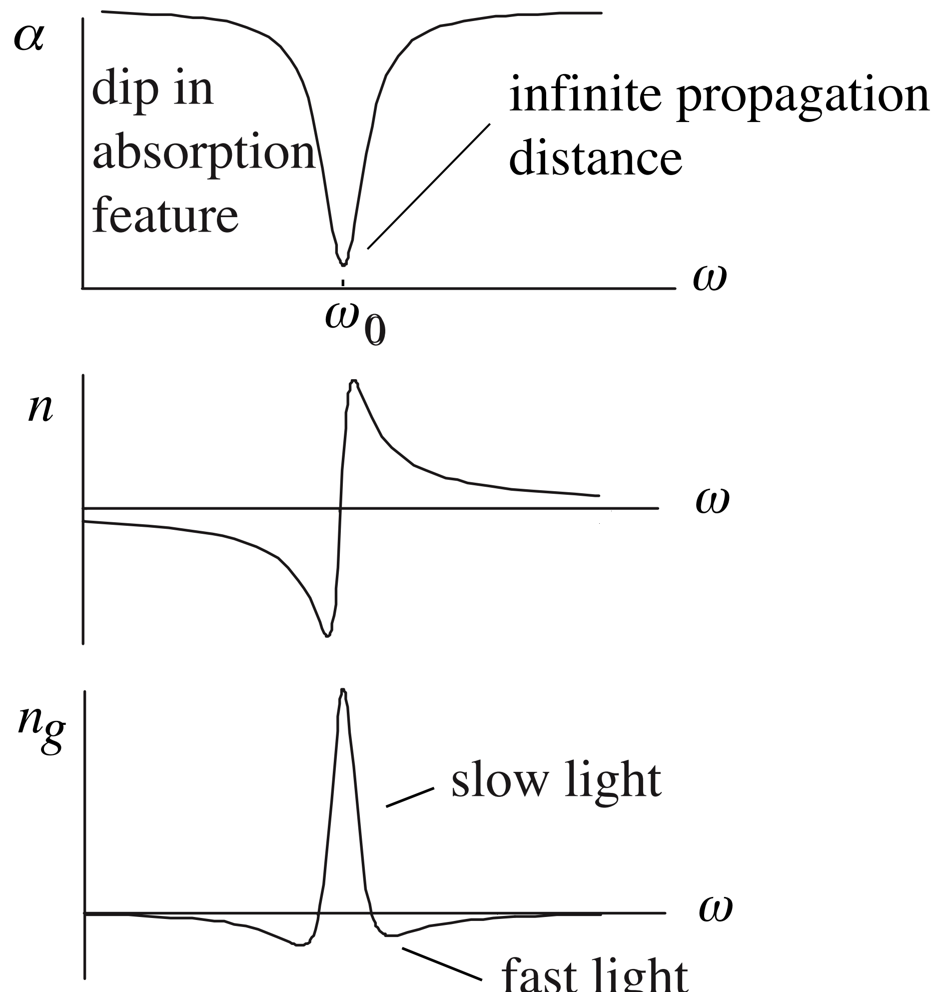
* Boyd, Gauthier, Gaeta, and Willner, PRA 2005

** 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?

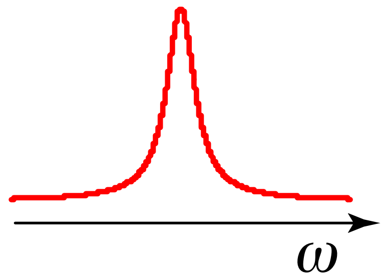
At the bottom of the dip in the absorpton, the absorption can in principle be made to vanish. There is then no limit on how long a propagation distance can be used.

This “trick”works only for slow light.

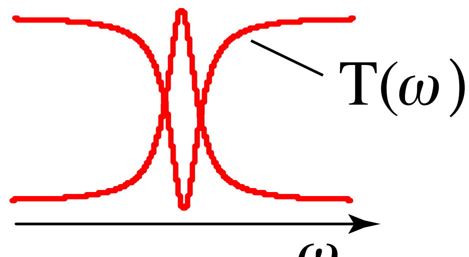


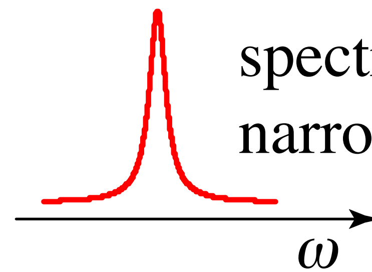
Influence of Spectral Reshaping
(Line-Center Operation, Dip in Gain or Absorption Feature)

input pulse



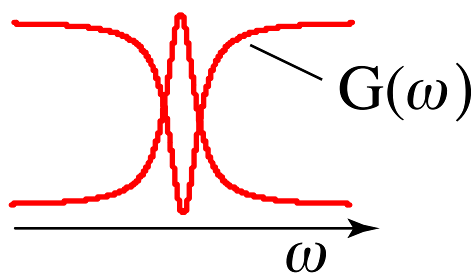
output pulse
slow-light

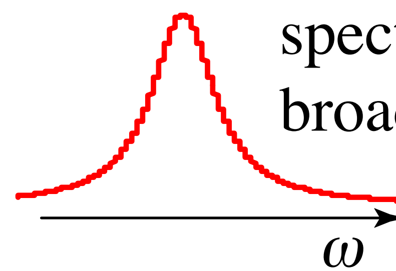




spectrally
narrowed pulse

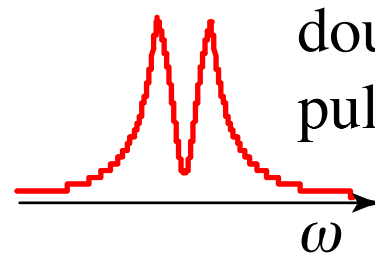
output pulse
fast-light





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.

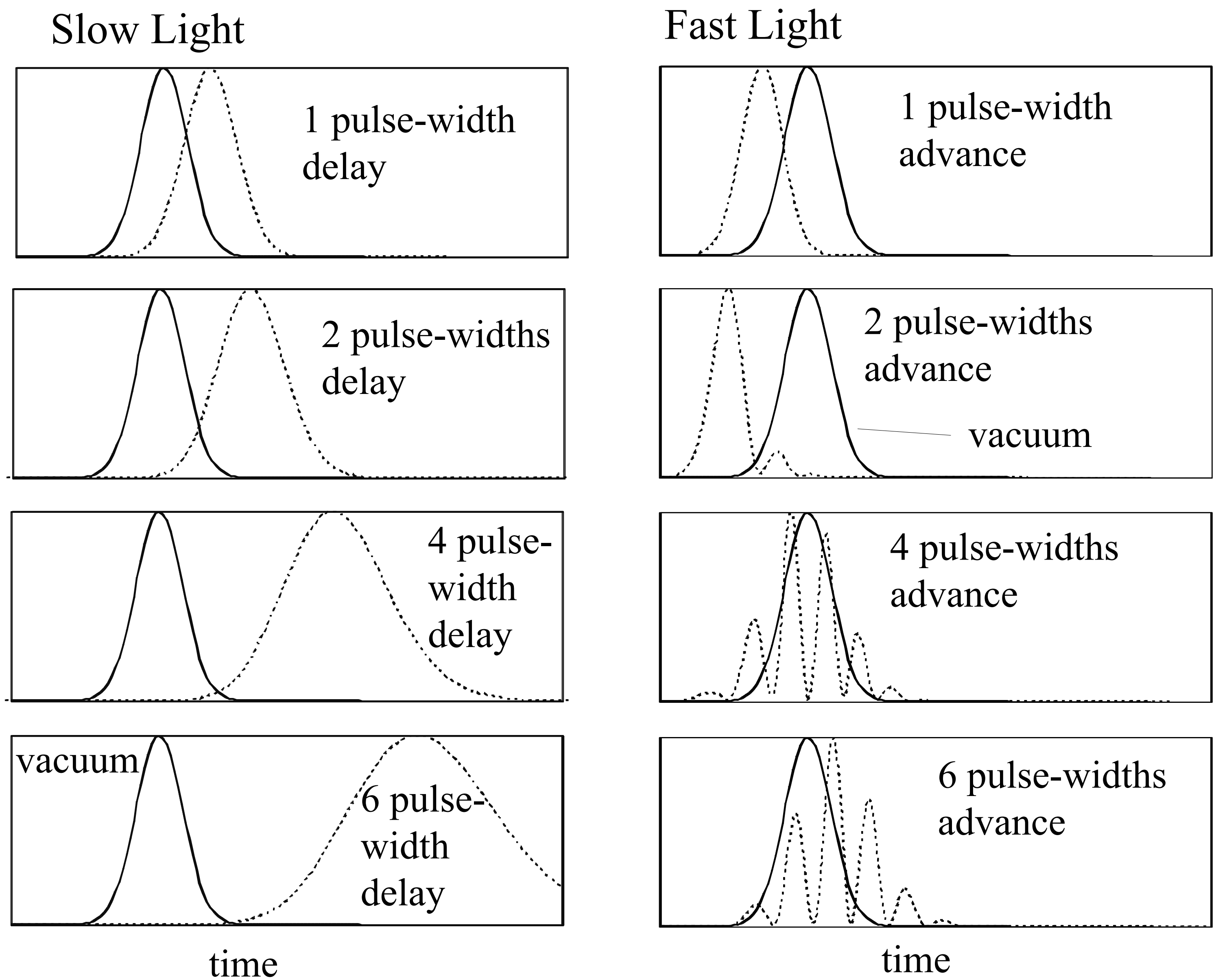
Numerical Results: Propagation through a Linear Dispersive Medium

Full (causal) model – solve wave equation with $P = \chi E$ 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



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Our Approach

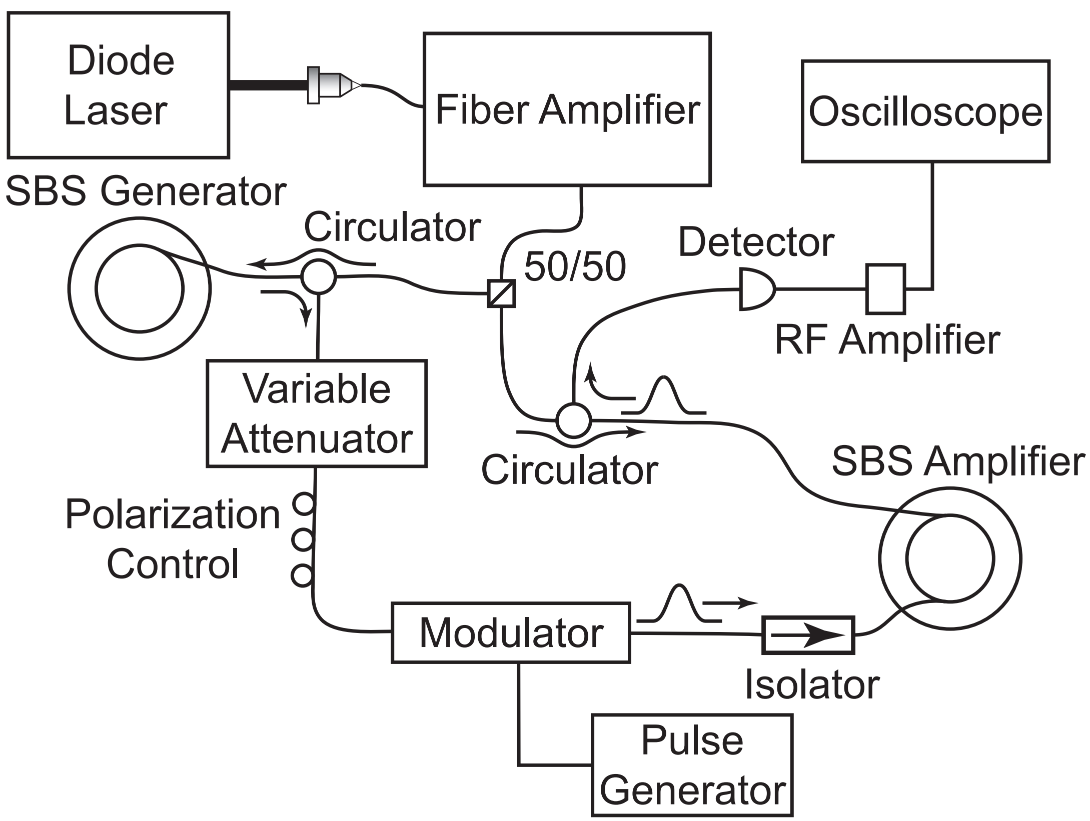
Slow light in a room-temperature solid-state material.

Systems under investigation:

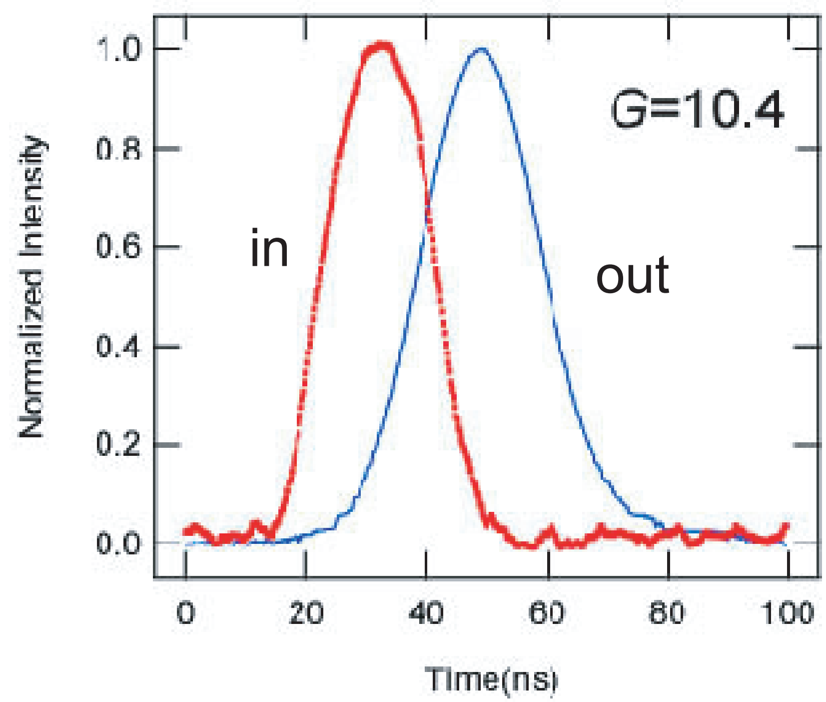
1. Stimulated Brillouin Scattering
2. Stimulated Raman Scattering
3. Wavelength Conversion and Dispersion
4. Coherent Population Oscillations
    a. Ruby and alexandrite
    b. Semiconductor quantum dots (PbS)
    c. Semiconductor optical amplifier
    d. Erbium-doped fiber amplifier

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



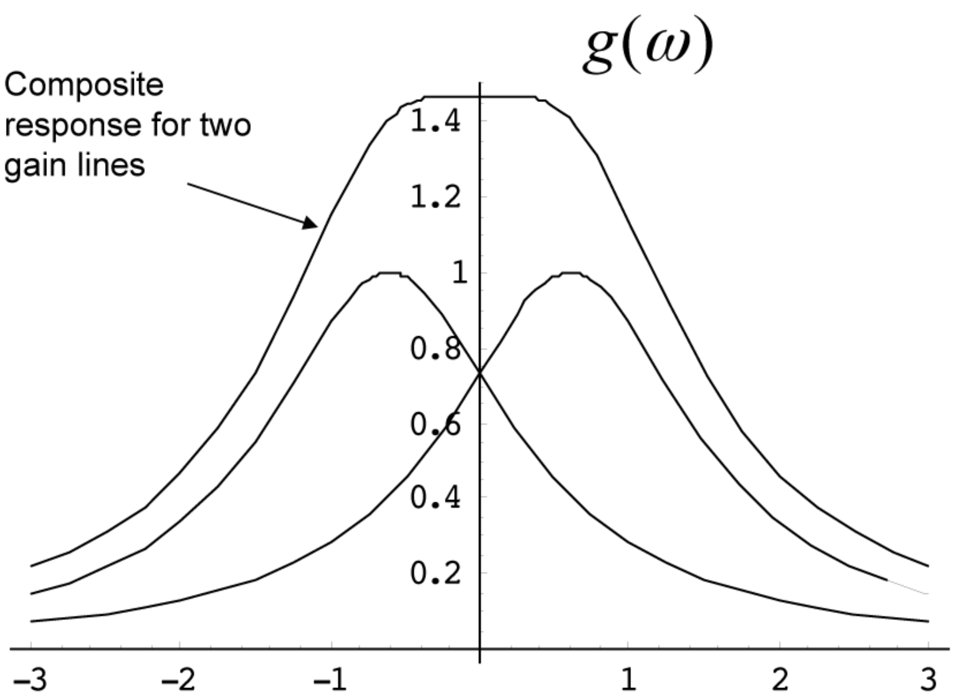
typical data

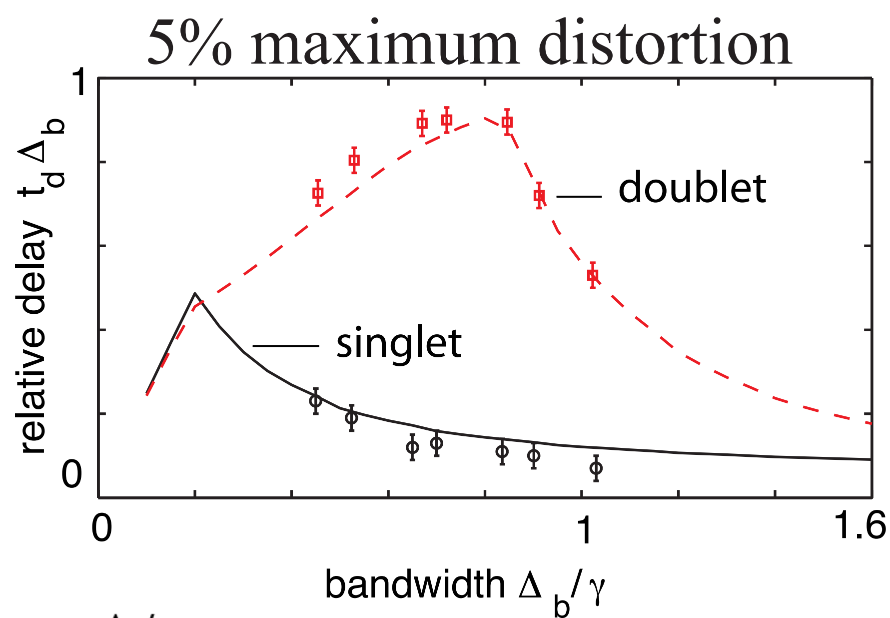


Okawachi, Bigelow, Sharping, Zhu, Schweinsberg, Gauthier, Boyd, and Gaeta Phys. Rev. Lett. 94, 153902 (2005).
Related results reported by Song, González Herráez and Thévenaz, Optics Express 13, 83 (2005).

Increasing the Bandwidth of a Slow Light Medium

- Use of a flattened gain line leads to significantly improved performance.
- Double gain line can cancel lowest-order contribution to pulse distortion



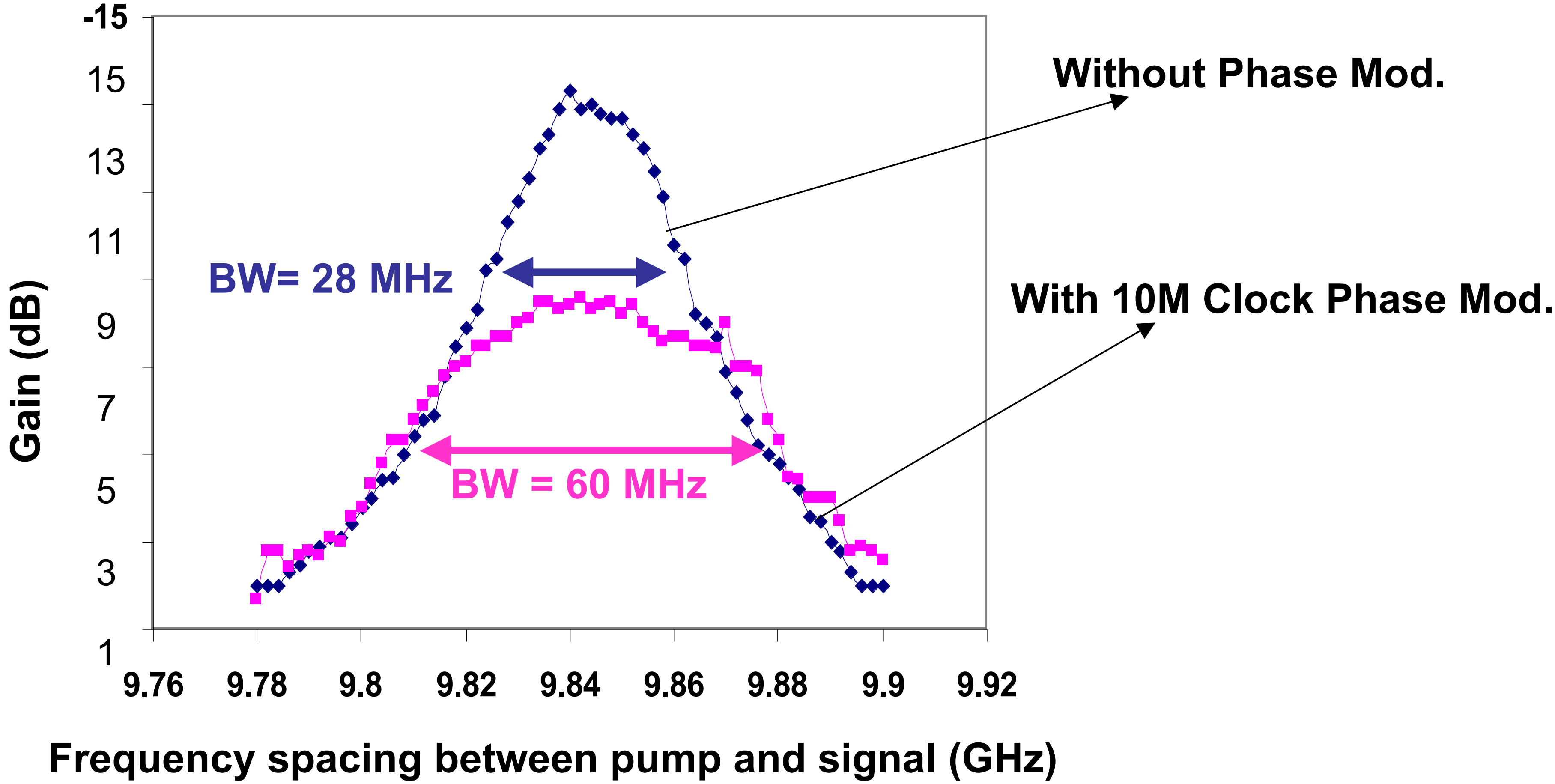


Δ/γ

Stenner et al., Opt. Express 13 9995 (2005)

Study of SBS Gain Spectrum Broadening

Expand the BW by phase modulating the pump

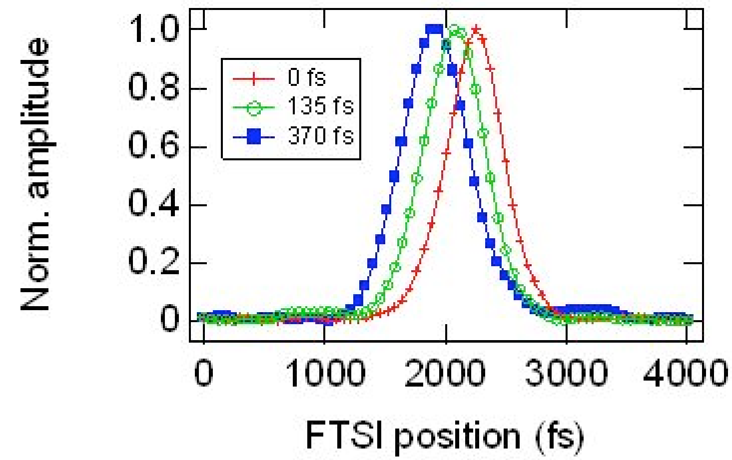


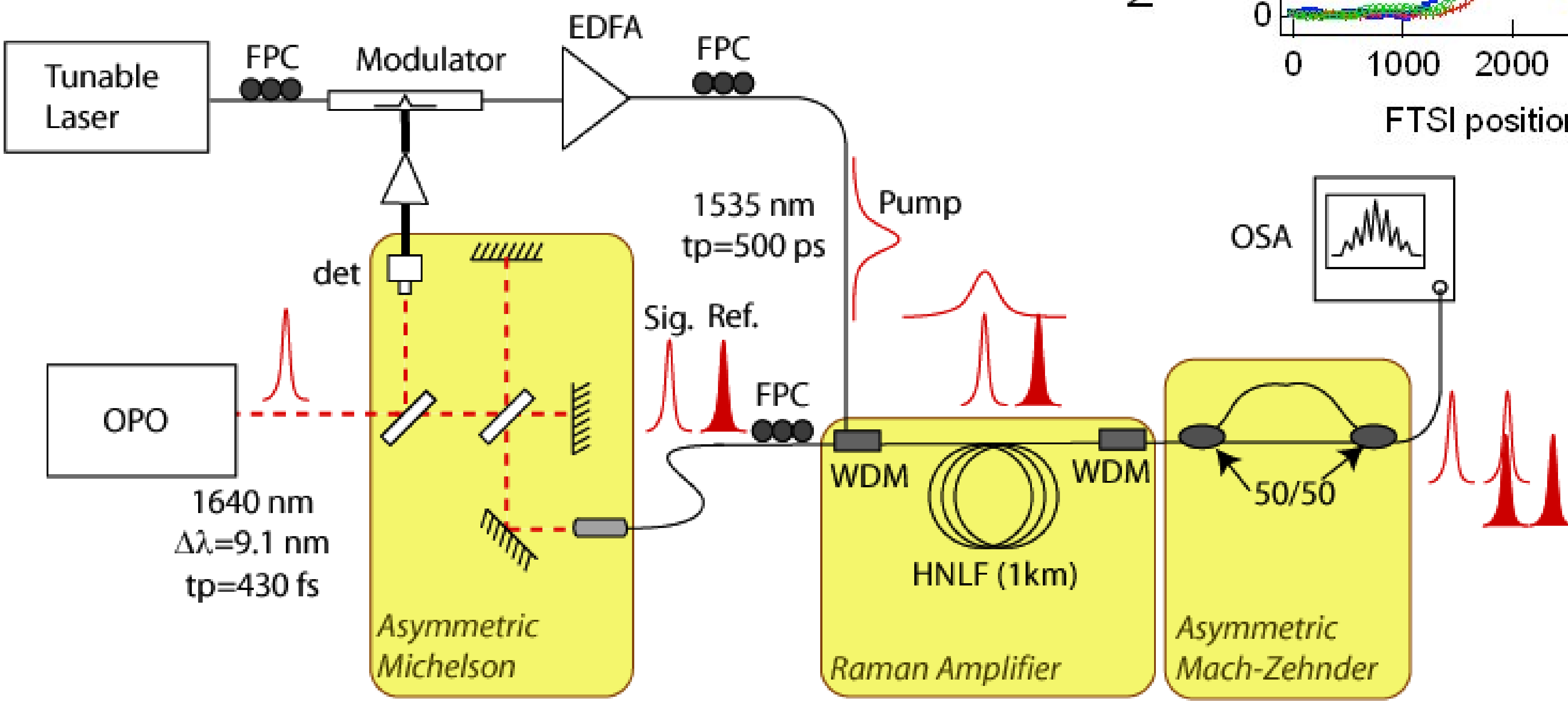
10 MHz clock phase modulating the pump

- Gain BW: 28 MHz → 60 MHz

Slow-Light by Stimulated Raman Scattering

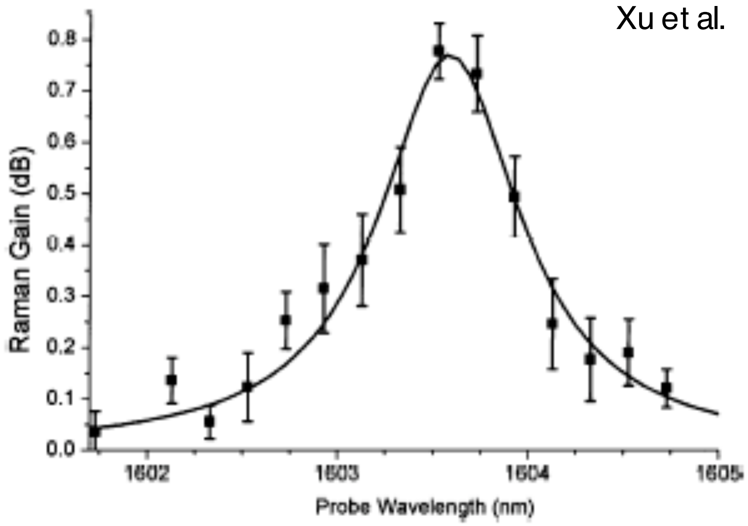
- The Raman linewidth (~3 THz) is adequate for foreseeable applications
- 370 fs delay observed for 430 fs input pulse (85% of pulse width)
- Alex Gaeta, Cornell

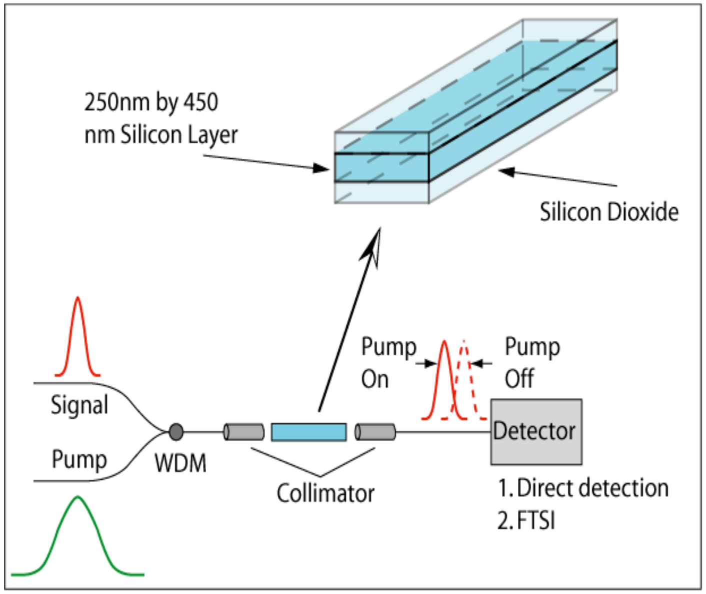




Slow Light Using SRS in a Silicon Nanostructure

- SRS medium is an 8-mm silicon-on-insulator (SOI) planar waveguide (Fabricated by M. Lipson's Group).
- The Raman linewidth is 1 nm and the gain coefficient g_R = 4.2 cm/GW in the waveguide.
- Up to 14 dB of Raman gain has been observed [Xu et al. (2004)].



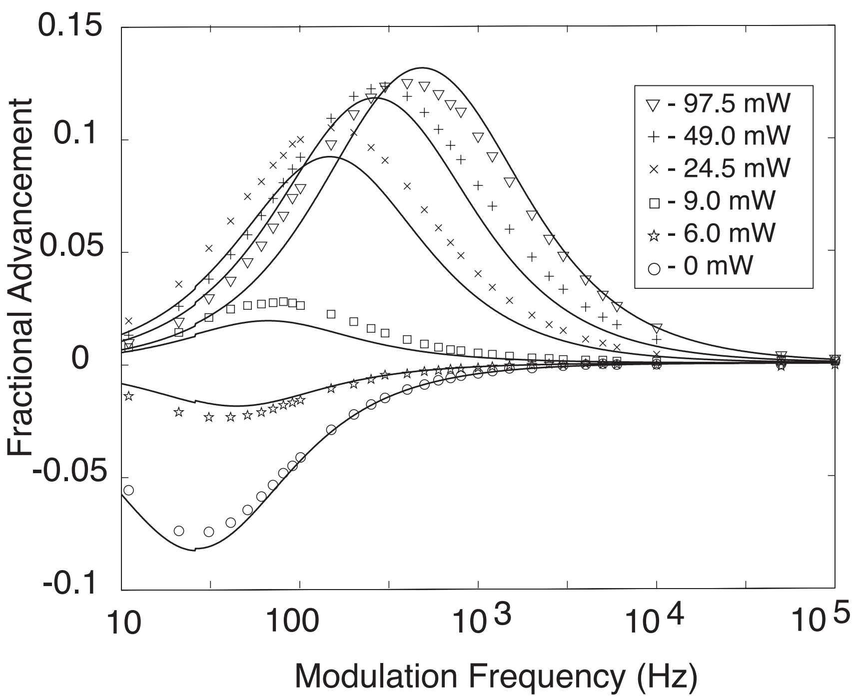


- System allows for flexibility in the operating wavelength (> 1 μm).
- Planar waveguide allows for CMOS-compatible all-optical tunable delay.

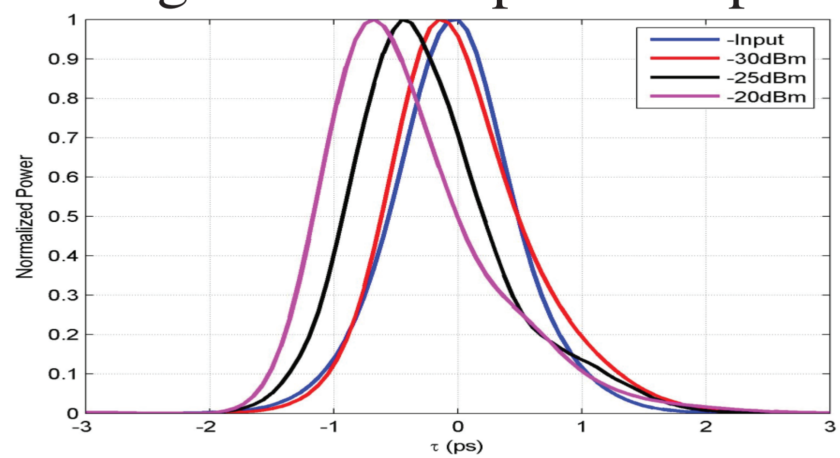
Slow Light via Coherent Population Oscillations

- 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.

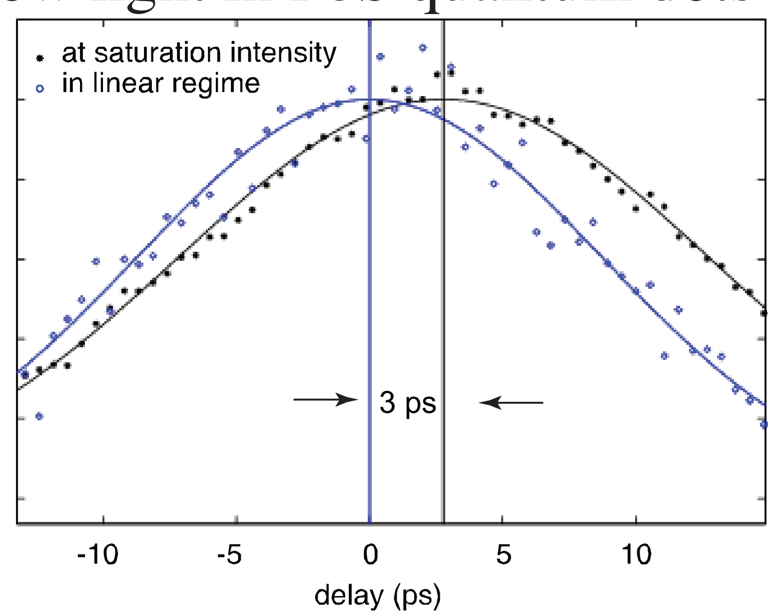
- Slow and fast light in an EDFA



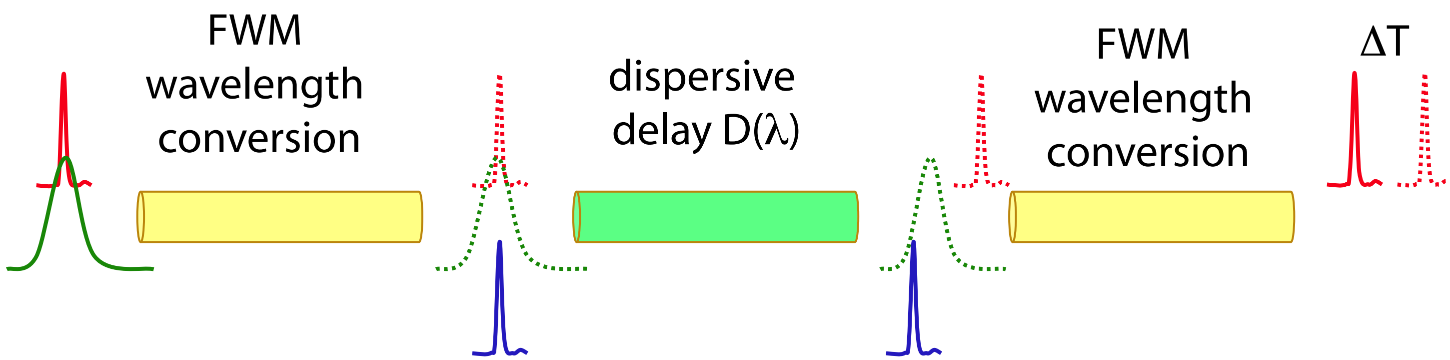
- Slow light in a SC optical amplifier



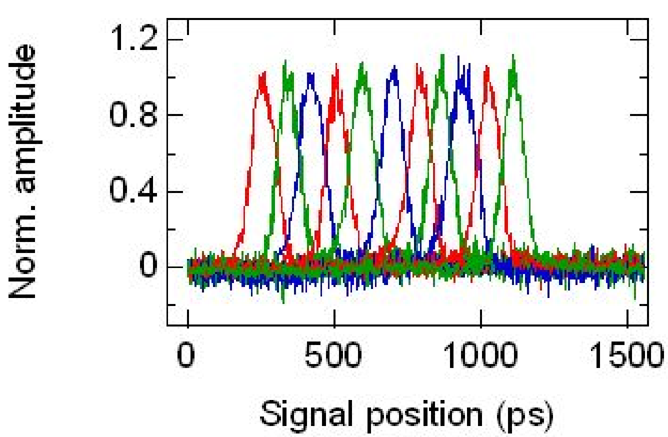
- Slow light in PbS quantum dots

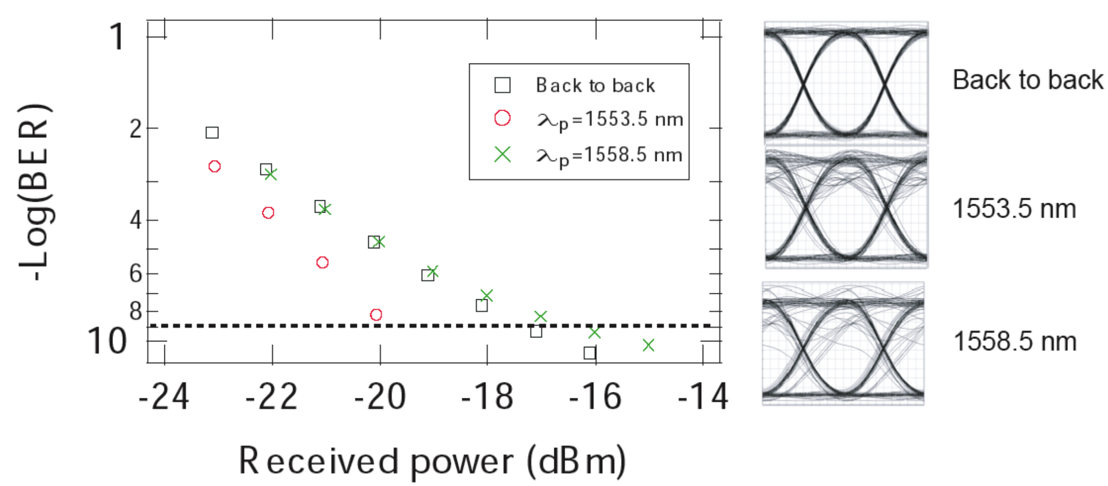


FWM-Dispersion Delay Method



- Results:
  - ⇒ 800 ps of delay
  - ⇒ Pulse quality is preserved
  - ⇒ No wavelength shift
  - ⇒ Phase information is preserved
  - ⇒ 10 Gb/s simulation implies a 3-dB received power penalty

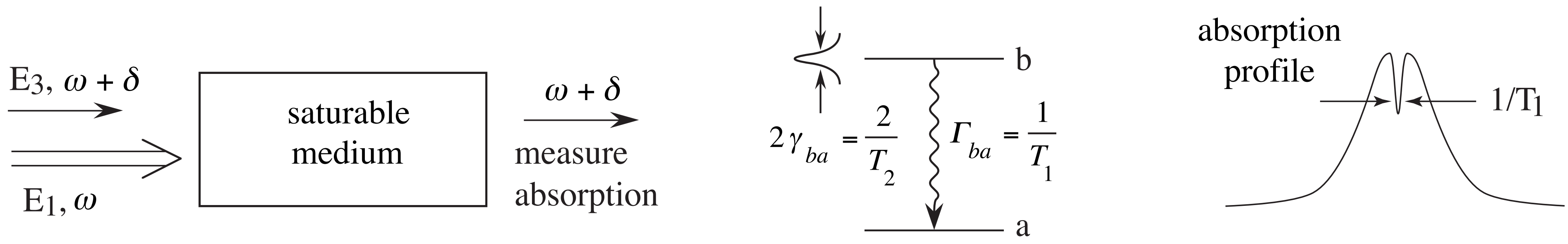




Slow Light in Optical Fibers: Applications of Slow Light in Telecom

1. Introduction, motivation, our research team
2. Modeling of slow light systems: maximum time delay
3. Progress in laboratory implementation of slow light methods
4. **Physics of slow-light interactions, causality issues**
5. Summary and conclusions

Slow Light via Coherent Population Oscillations

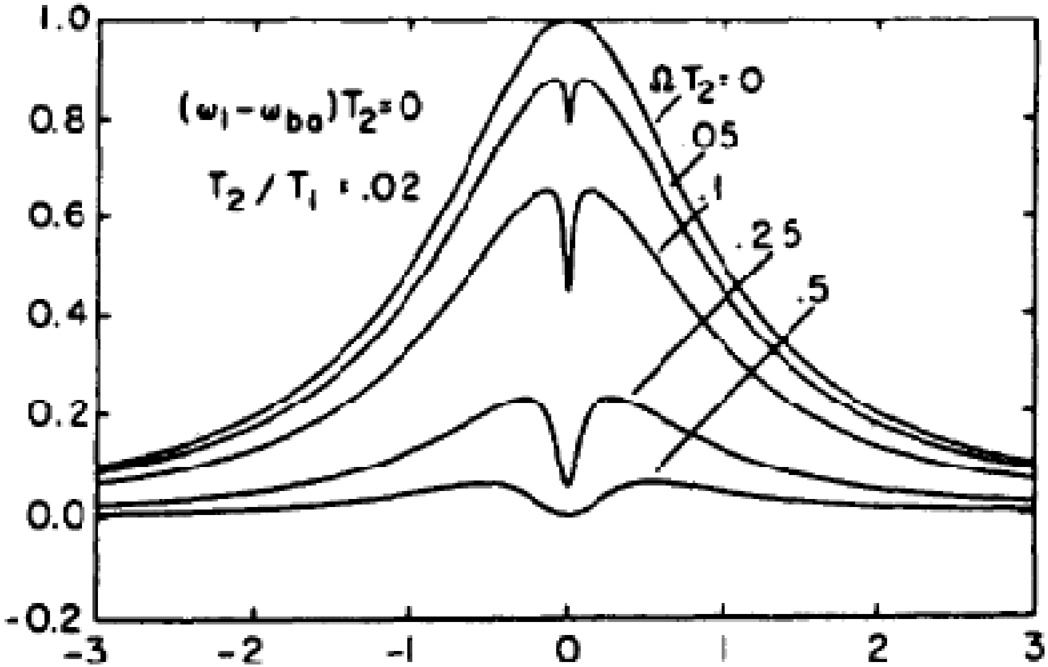


- Ground state population oscillates at beat frequency δ (for $\delta < 1/T_1$).
- Population oscillations lead to decreased probe absorption (by explicit calculation), even though broadening is homogeneous.
- Rapid spectral variation of refractive index associated with spectral hole leads to large group index.
- Ultra-slow light ($n_g > 10^6$) observed in ruby and ultra-fast light ($n_g = -4 \times 10^5$) observed in alexandrite by this process.
- Slow and fast light effects occur at room temperature!

PRL 90,113903(2003); Science, 301, 200 (2003)

Spectral Holes in Homogeneously Broadened Materials

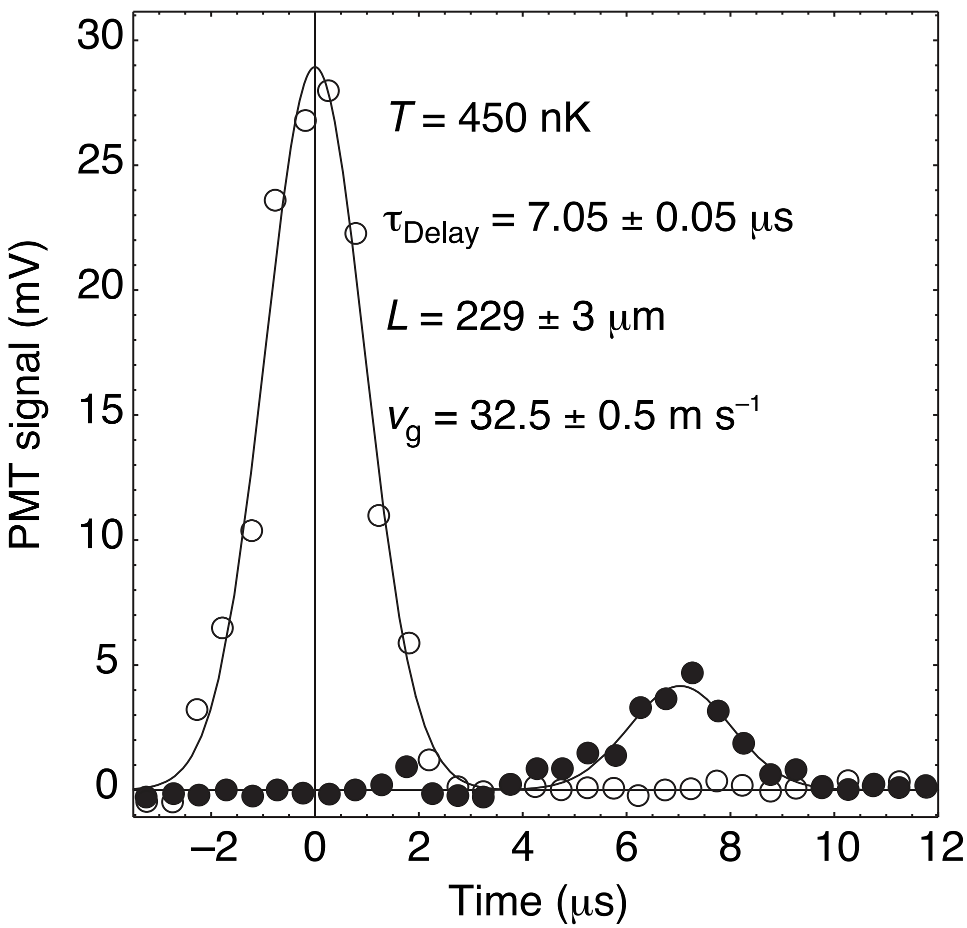
Occurs only in collisionally broadened media ($T_2 << T_1$)



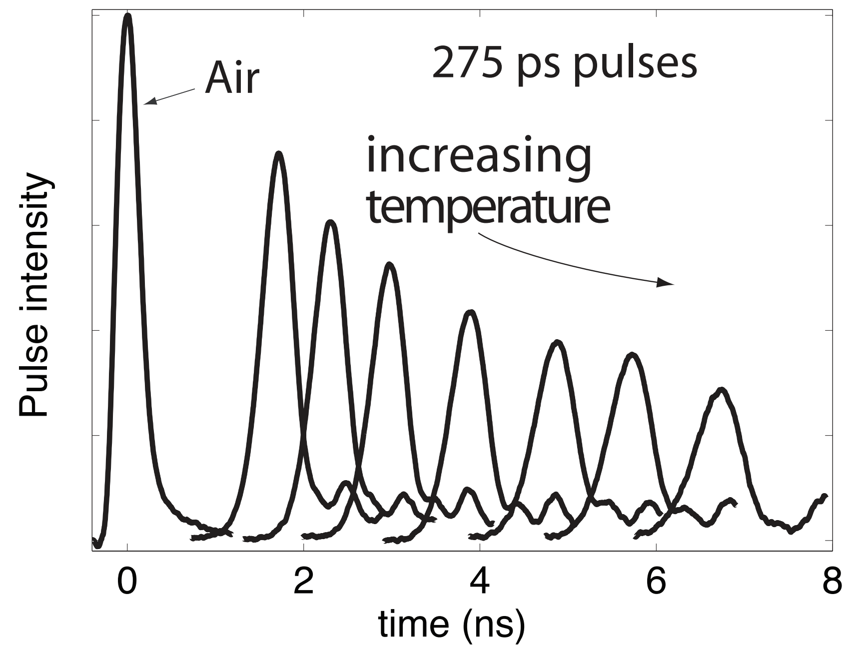
pump-probe detuning (units of $1/T_2$)

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

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

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**

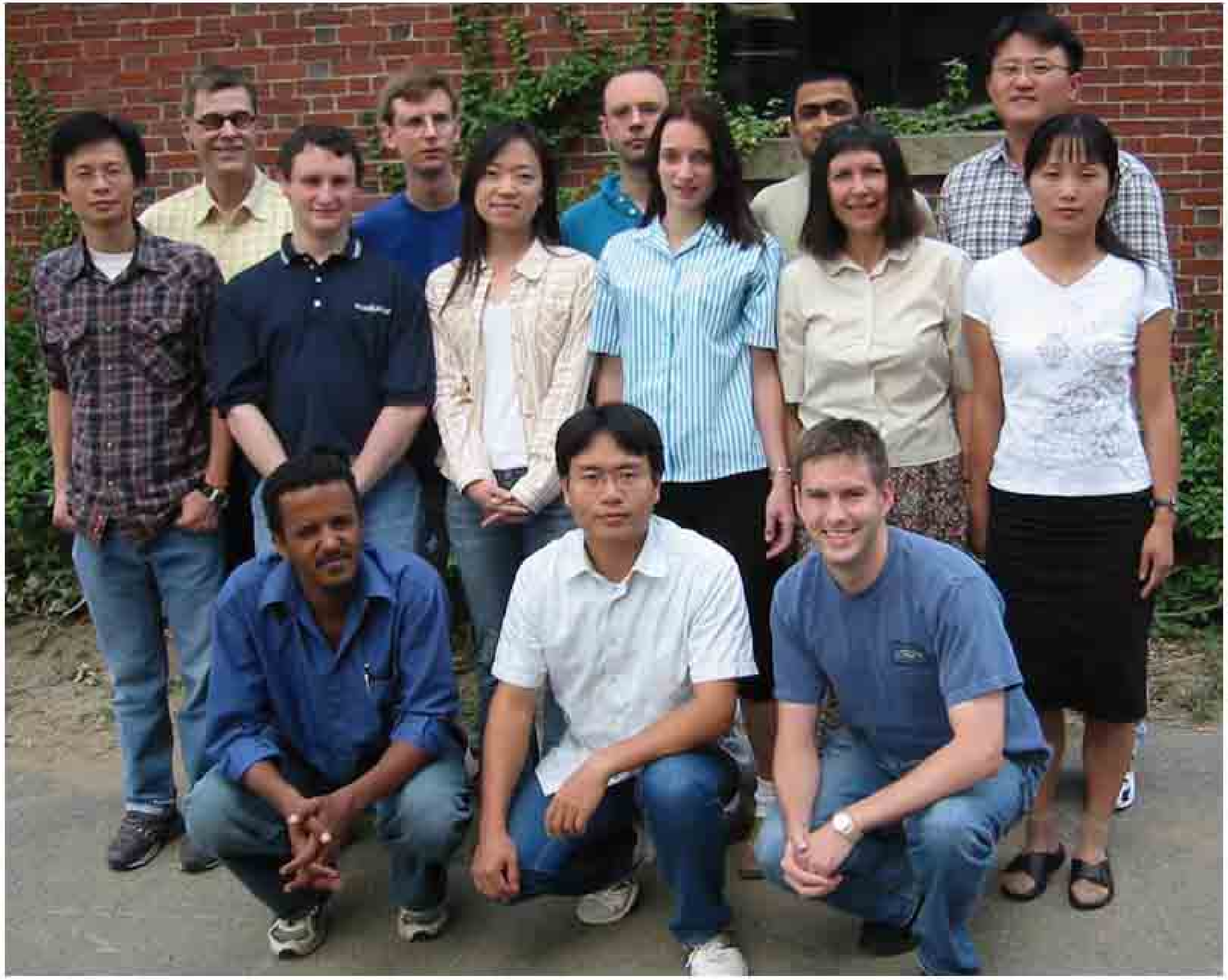
Wen I Wang

Kam **Wai** Chan

Not to mention

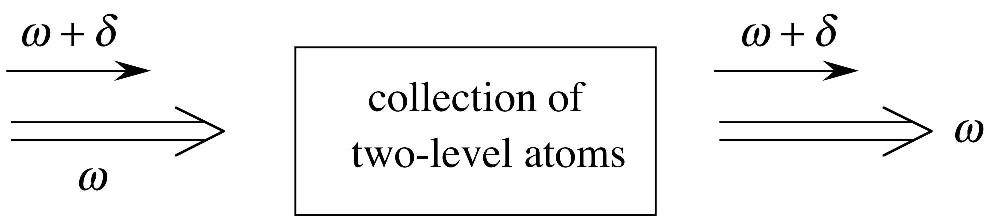
Lene **Hau**

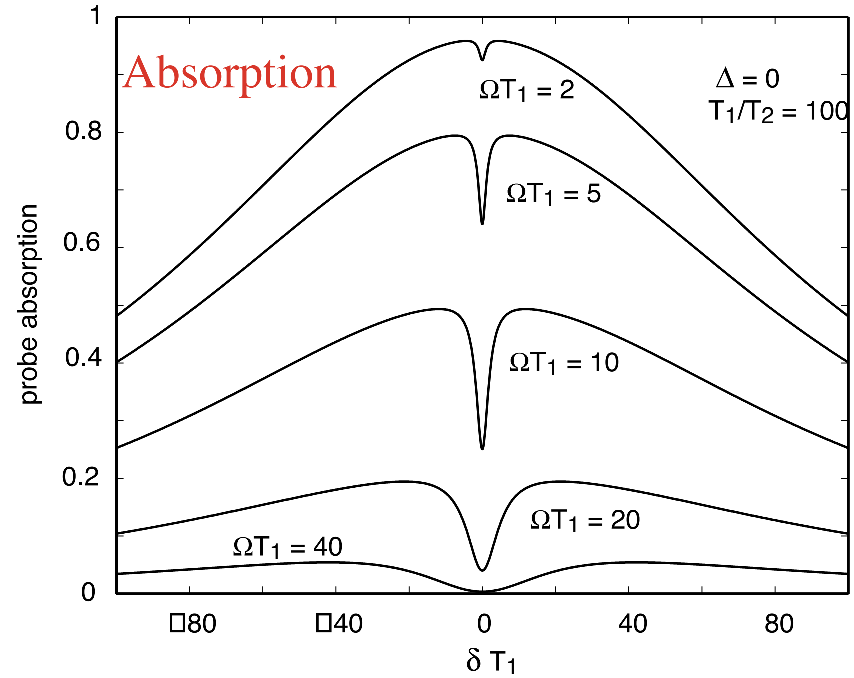
Special Thanks to My Students and Research Associates



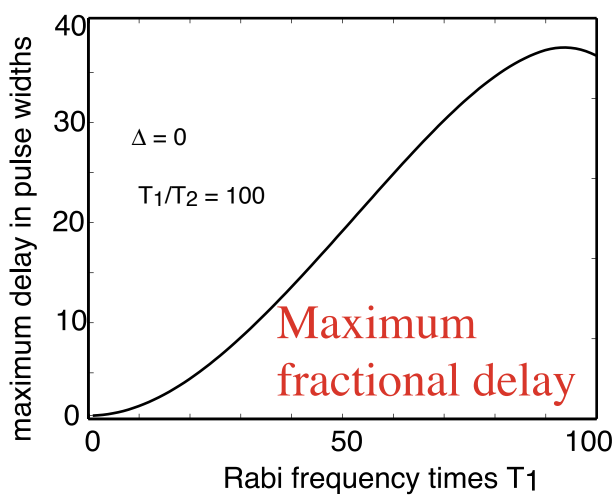
Thank you for your attention!

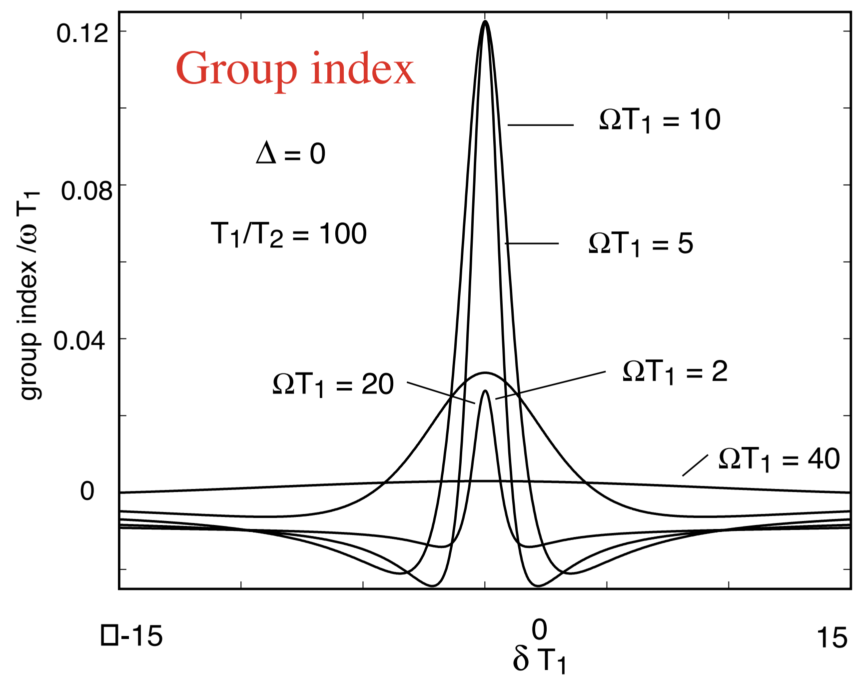
Prospects for Large Fractional Delays Using CPO





Strong pumping leads to high transparency, large bandwidth, and increased fractional delay.





Boyd et al., Laser Physics 2005.