Slowing Down the Speed of Light

Applications of "Slow" and "Fast" Light

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with Mathew Bigelow, Nick Lepeshkin, Aaron Schweinsberg,
Petros Zerom, Giovanni Piredda, Zhimin Shi, Heedeuk Shin, and others.

Presented at SPIE, July 2005.

Interest in Slow Light

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

Fundamentals of optical physics

Velocity of light and the historical development of physics

Optical delay lines, optical storage, optical memories

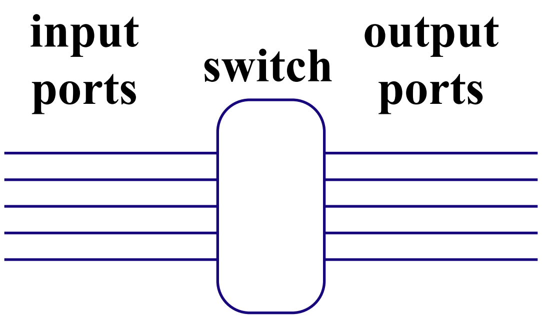
Implications for quantum information

And what about fast light ($v > c$ or negative)?

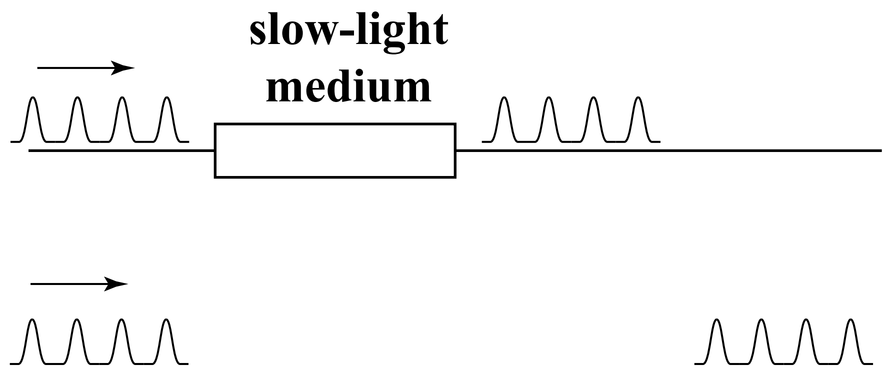
Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.

Slow Light and Optical Buffers

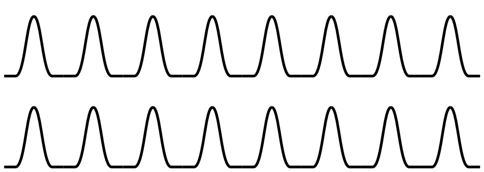
All-Optical Switch



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

Challenge/Goal

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

Solution: Slow light enabled by coherent population oscillations (a quantum coherence effect that is relatively insensitive to dephasing processes).

Slow Light in Ruby

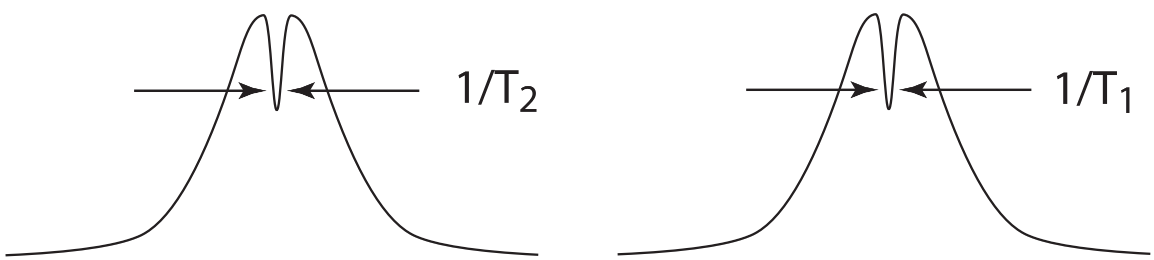
Need a large dn/dω. (How?)

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

Well-known (to the few people how know it well) how to do so:

Make use of "spectral holes" due to population oscillations.

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



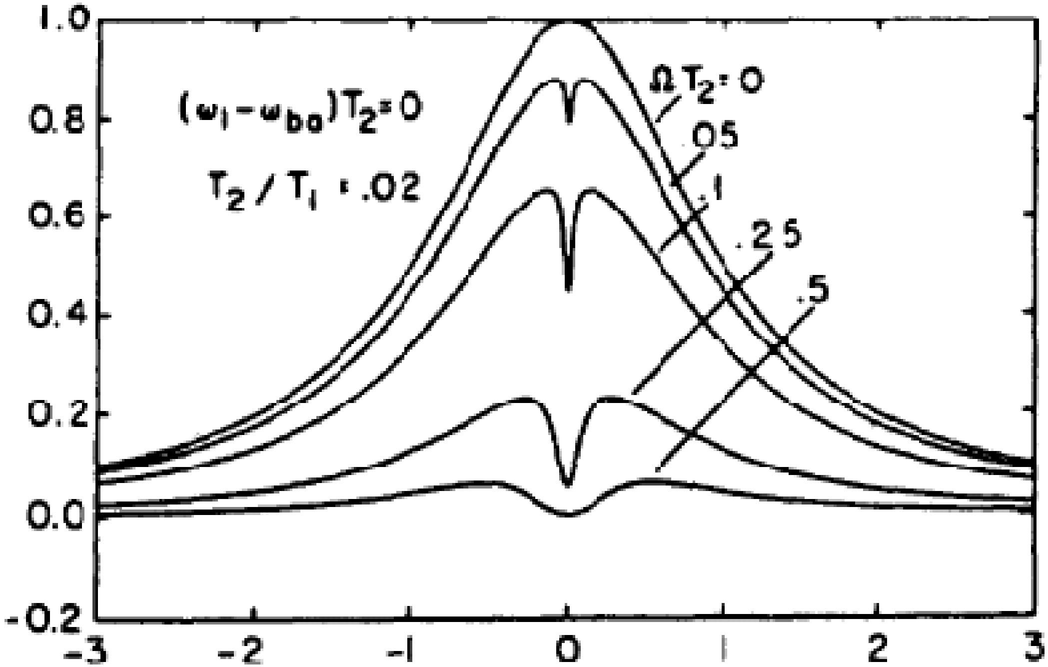
inhomogeneously broadened medium

homogeneously broadened medium (or inhomogeneously broadened)

PRL 90,113903(2003); see also news story in Nature.

Spectral Holes in Homogeneously Broadened Materials

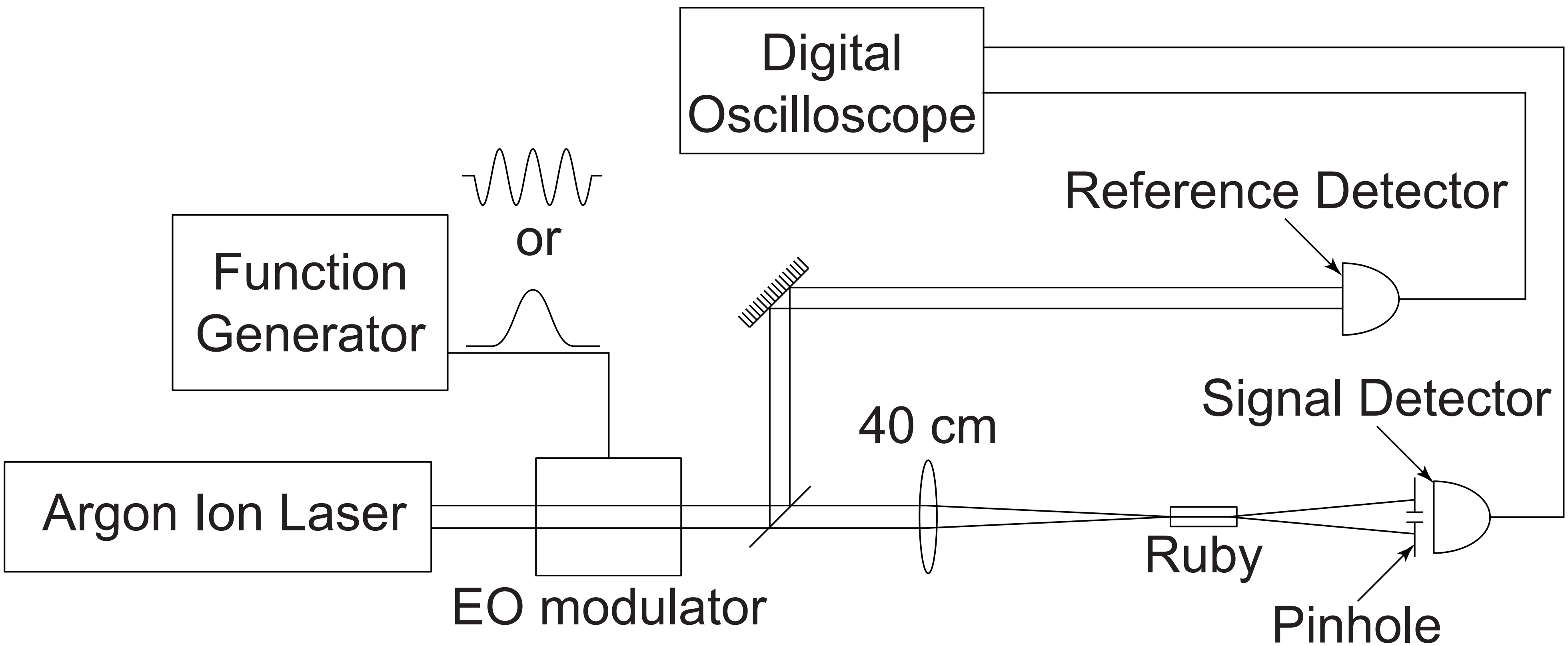
Occurs only in collisionally broadened media ($T_2 << T_1$)



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

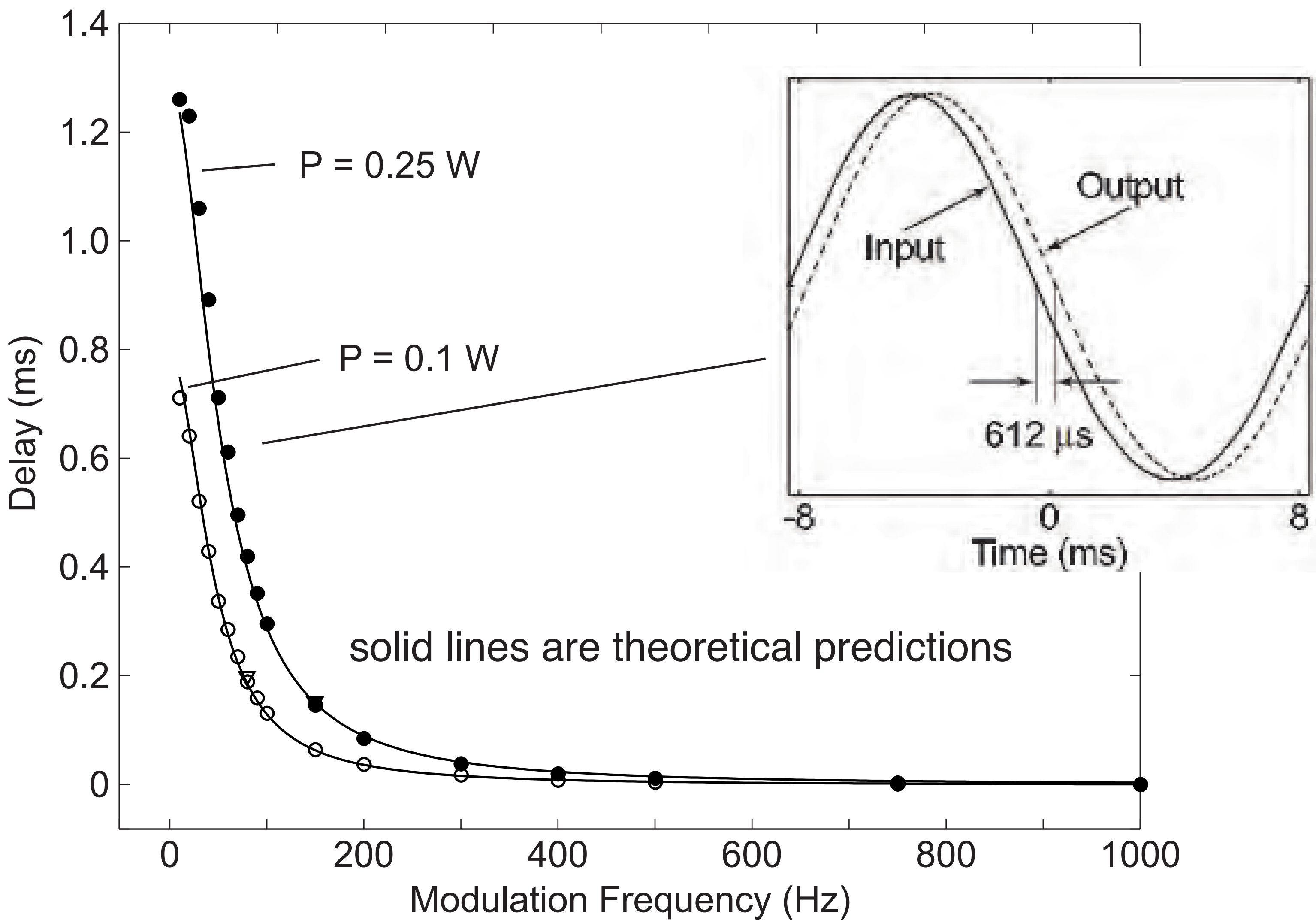
Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

Slow Light Experimental Setup



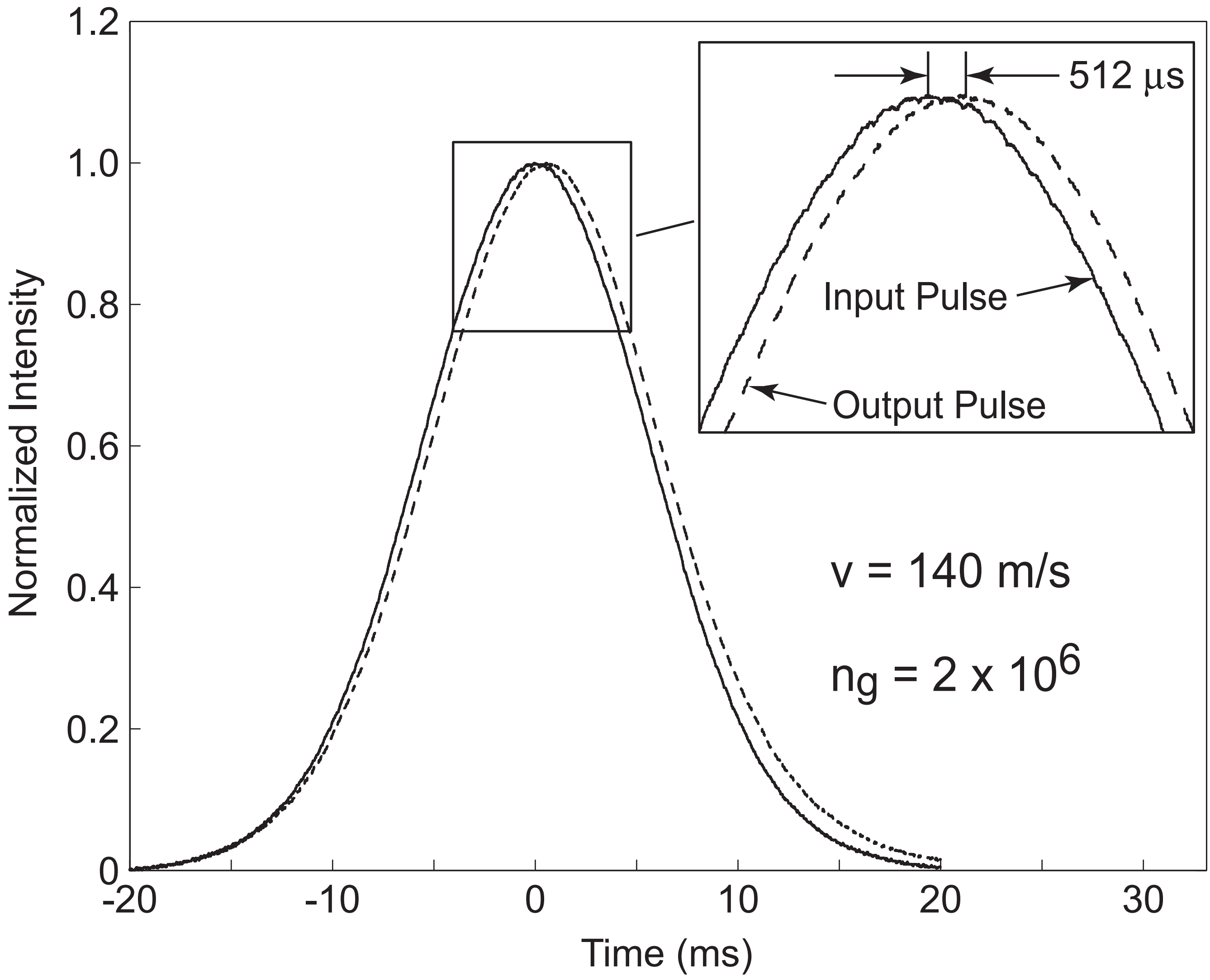
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



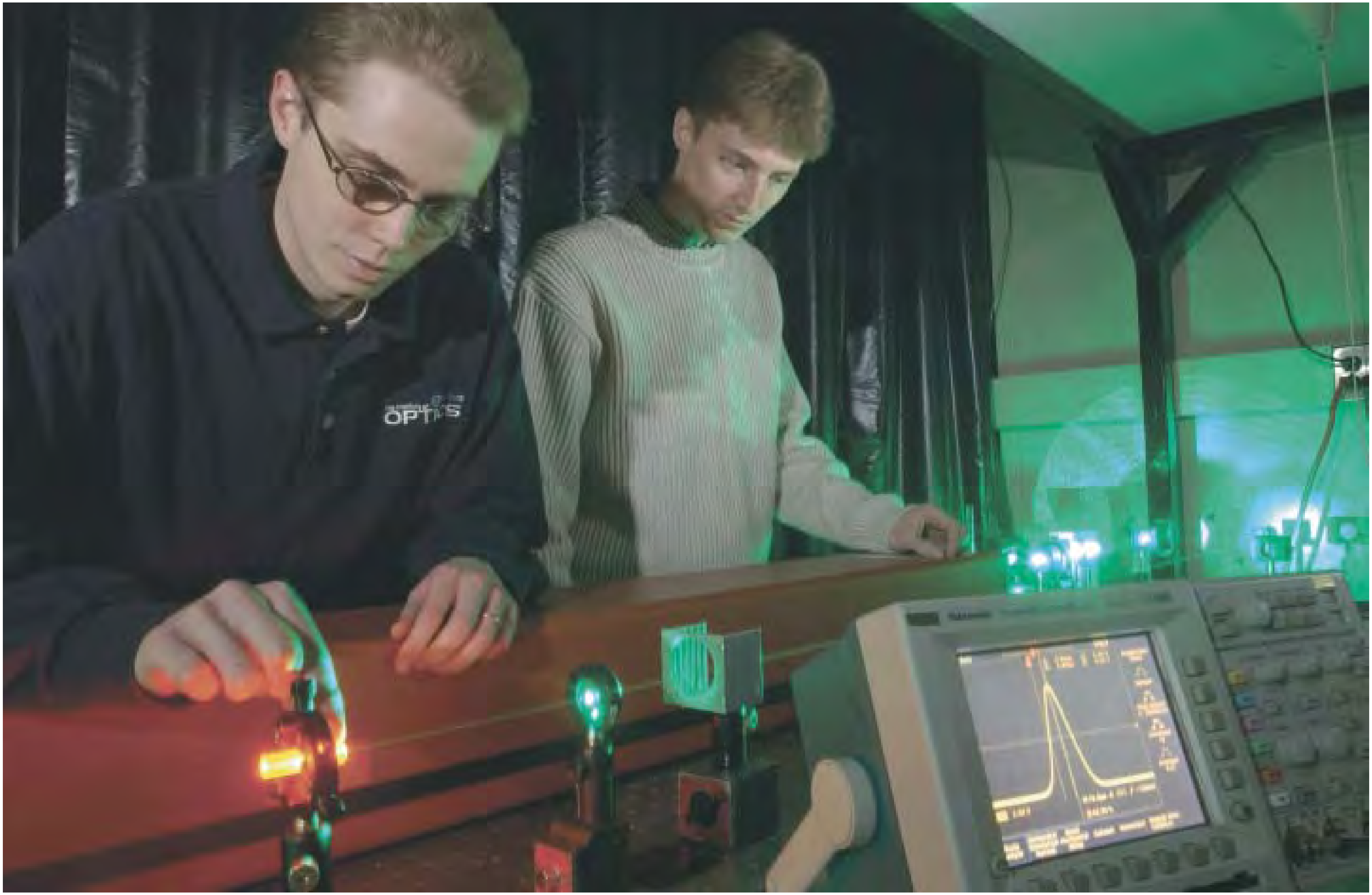
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

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

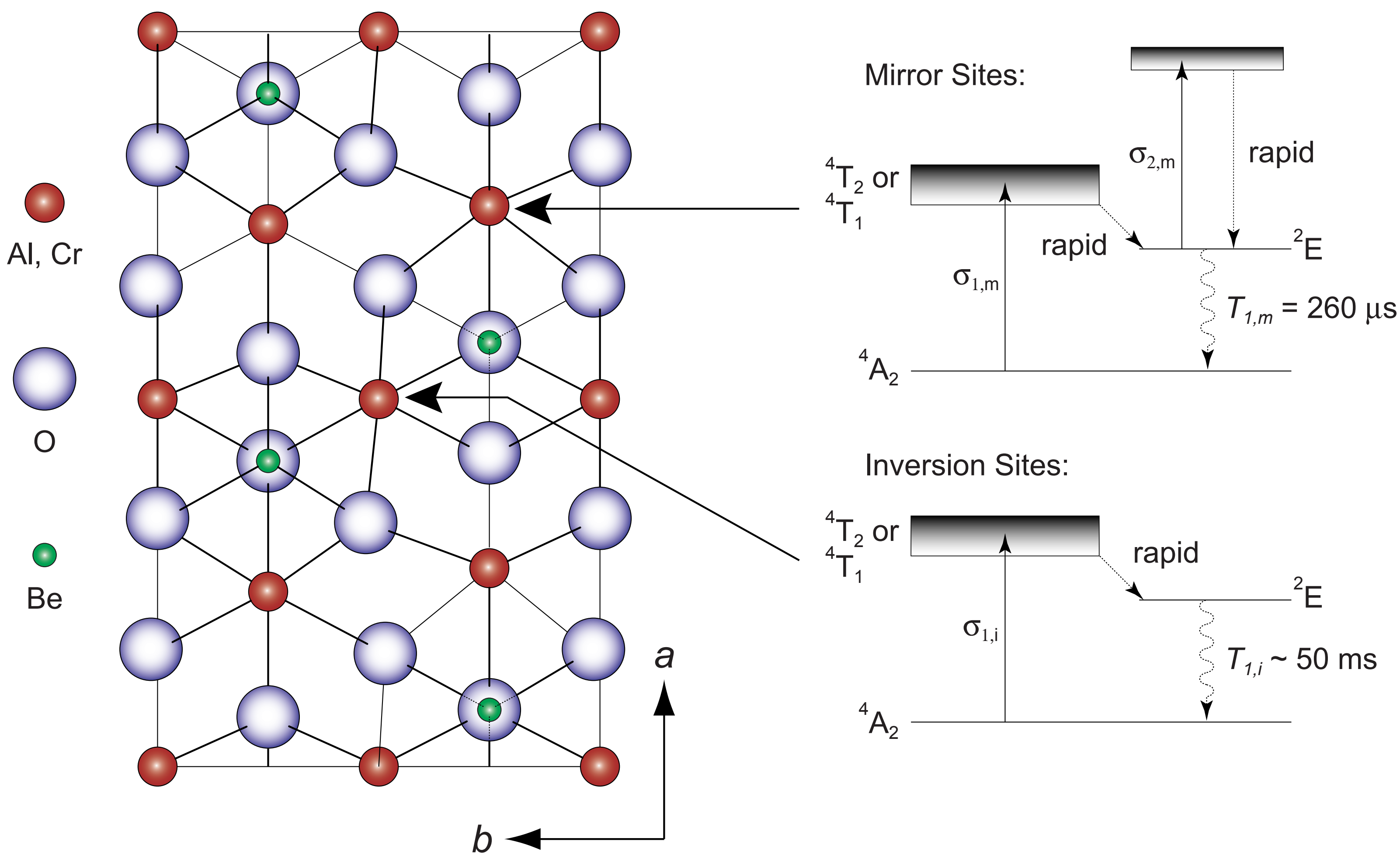
Laser need not be frequency stabilized

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

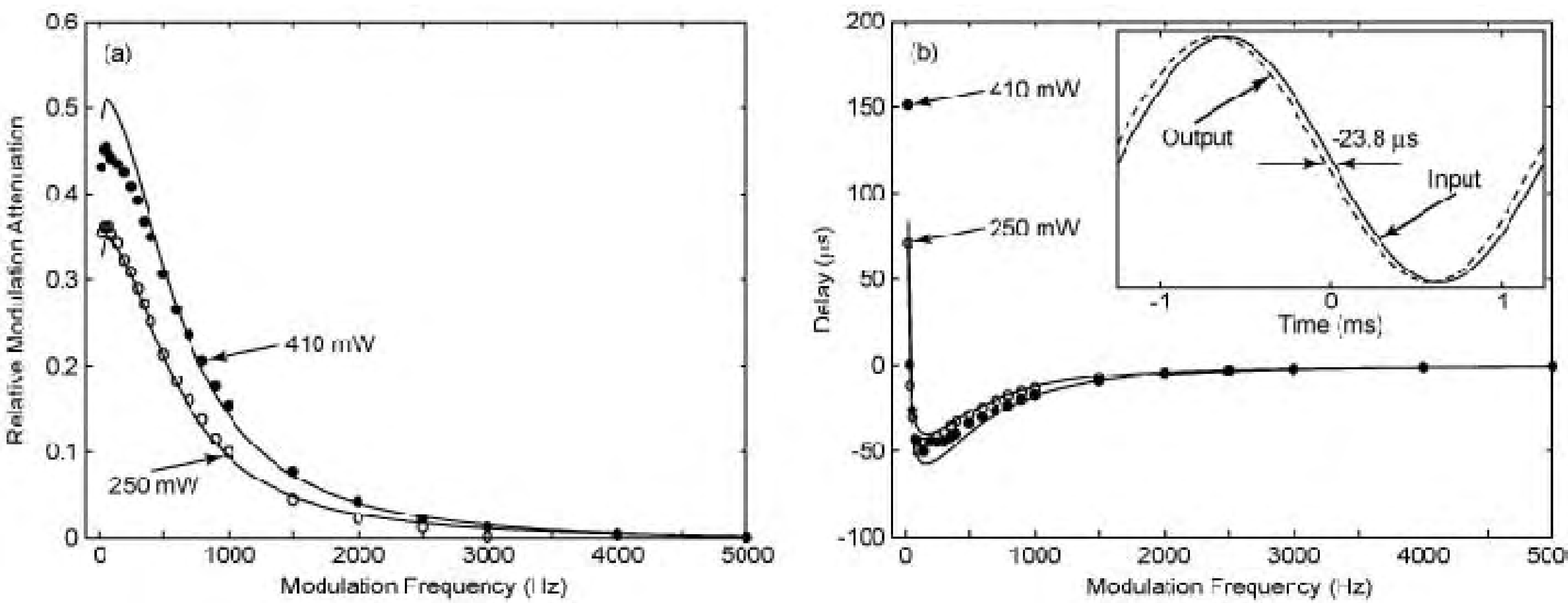


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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 paraxial 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.

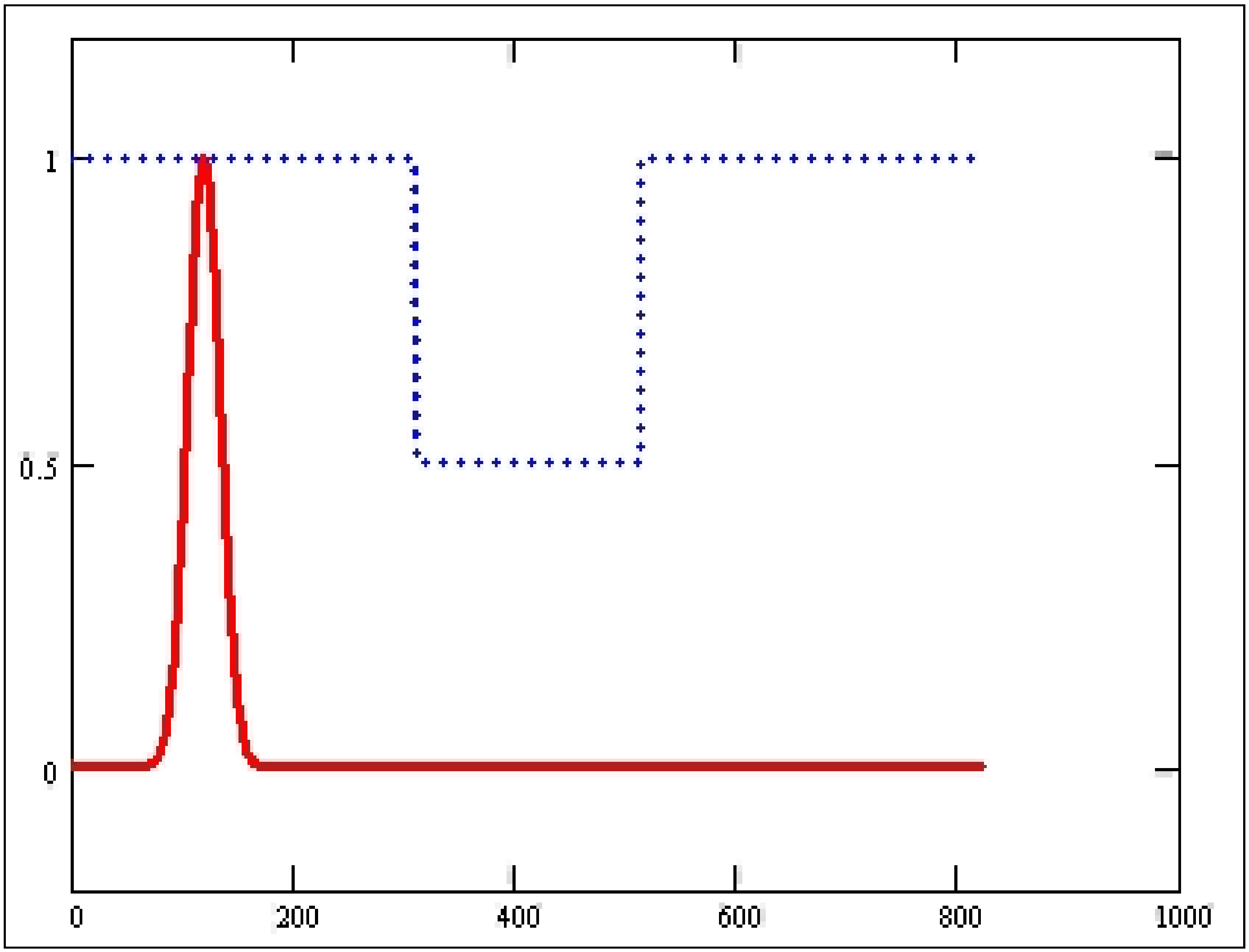
Assume an input pulse with a Gaussian temporal profile.

Study three cases:

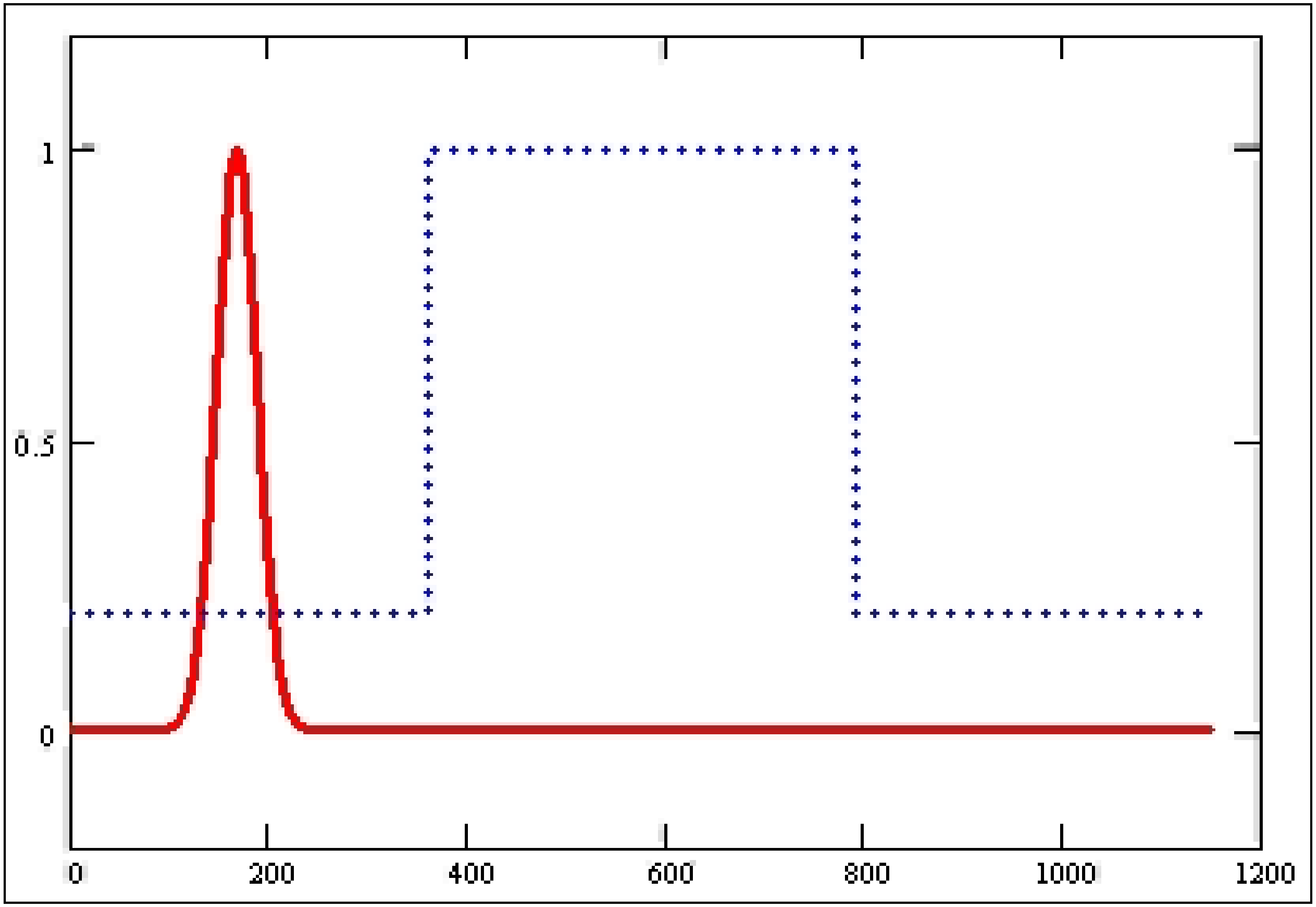
Slow light $v_g = 0.5\ c$

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

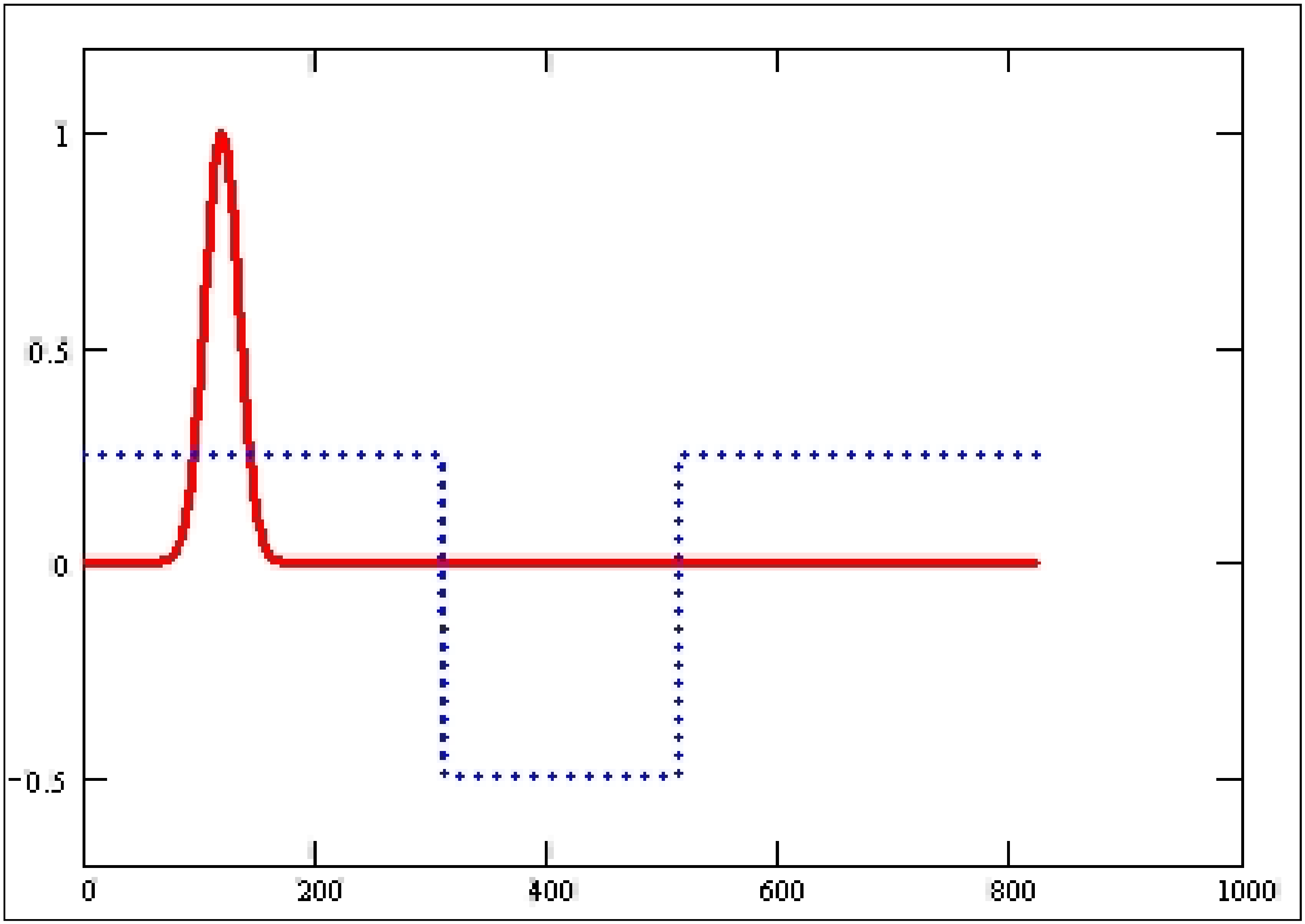
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



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



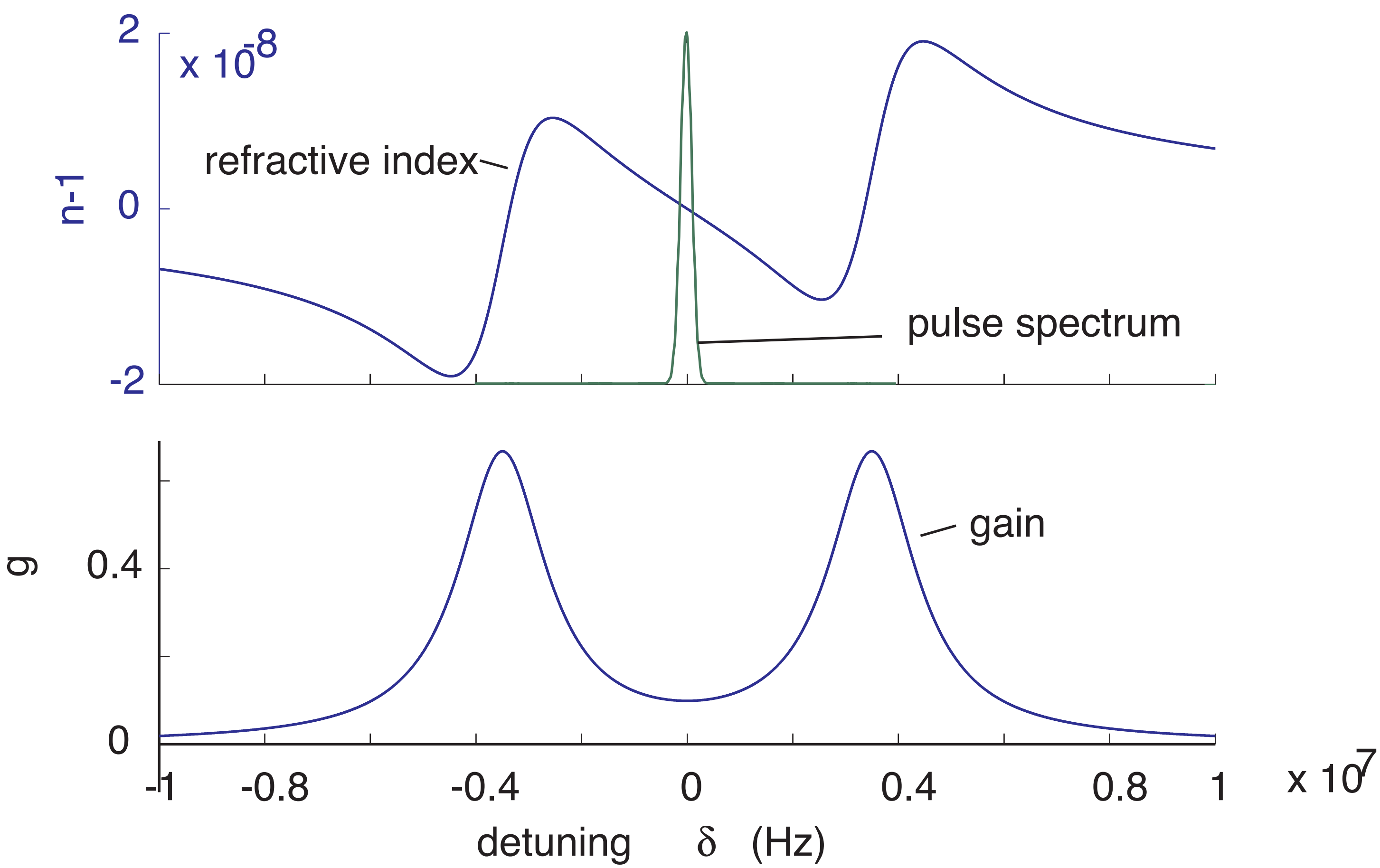
Pulse Propagation through a Fast-Light Medium (n_g = -.5, v_g = -2 c)



Are these predictions physical?
(We simply postulated a negative group velocity)

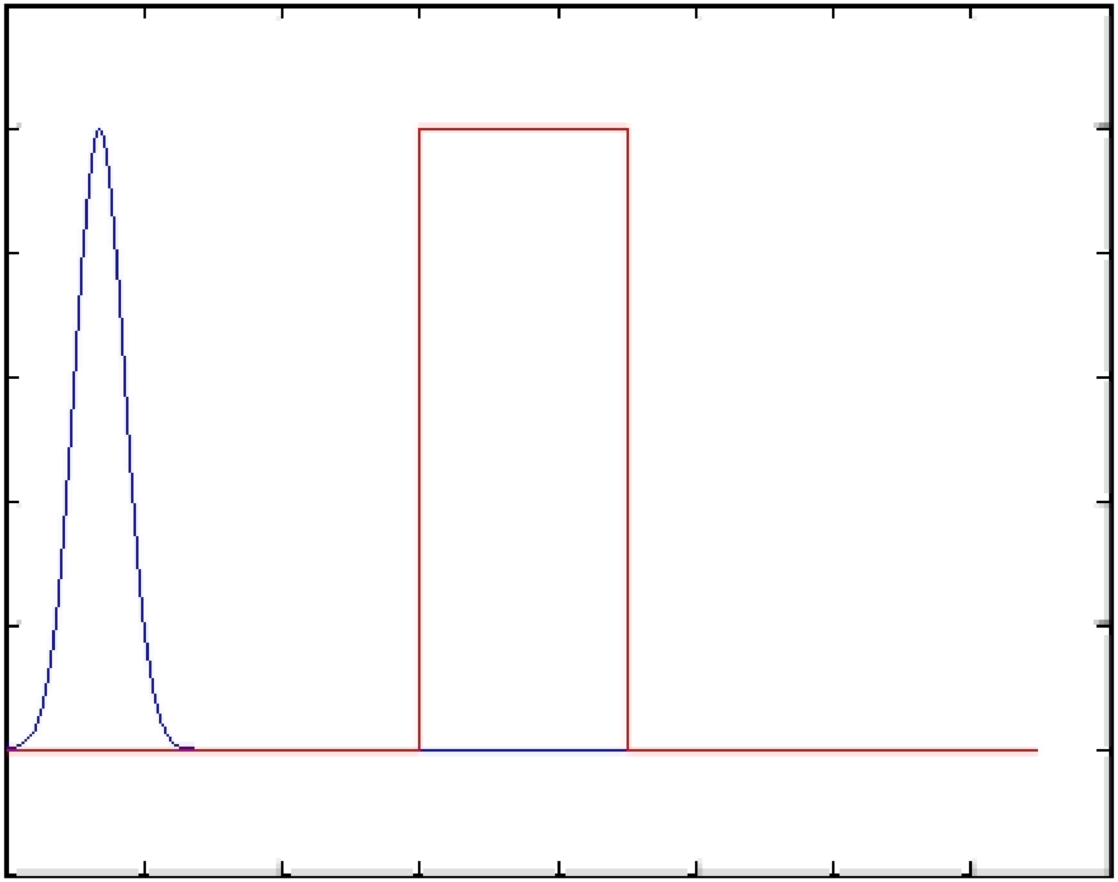
Consider a causal medium, for which Re *n* and Im *n* obey KK relations

Treat a gain doublet, which leads to superluminal effects*



* see also Chiao, Steinberg, Wang, Kuzmich, Gauthier, etc.

Superluminal Pulse Propagation through a Causal Medium



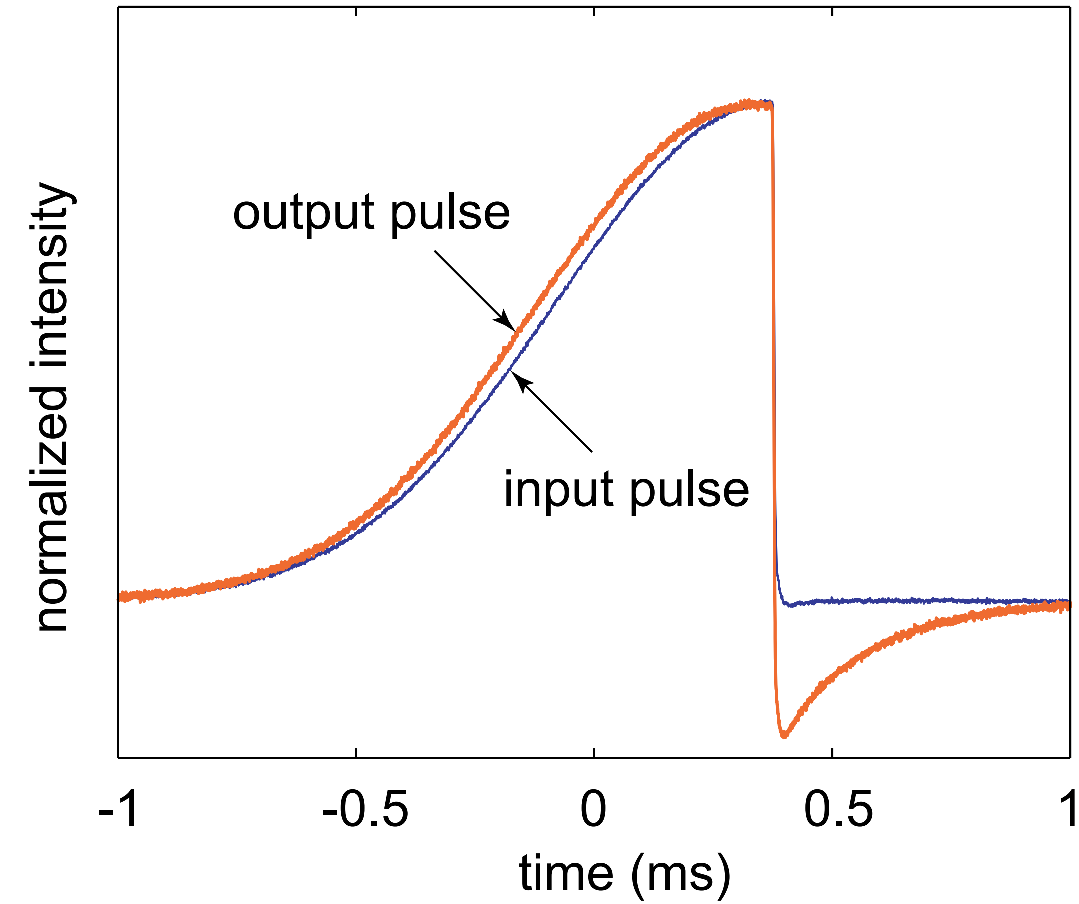
$$\chi(\omega) = \frac{A}{(\omega_0 - \Delta\omega) - \omega - i\Gamma} + \frac{A}{(\omega_0 + \Delta\omega) - \omega - i\Gamma}$$

pulse duration = 10 μs

$\Gamma = (2\pi)\ 0.25$ kHz $\quad A = 250$ / s

$\Delta\omega = (2\pi)$ 100 MHz = half frequency separation of gain lines

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 velocity)

Limits on the Time Delay Induced by Slow-Light Propagation

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ECE Dept, USC

See also Phys. Rev. A 71, 023801 (2005)

Motivation: 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.

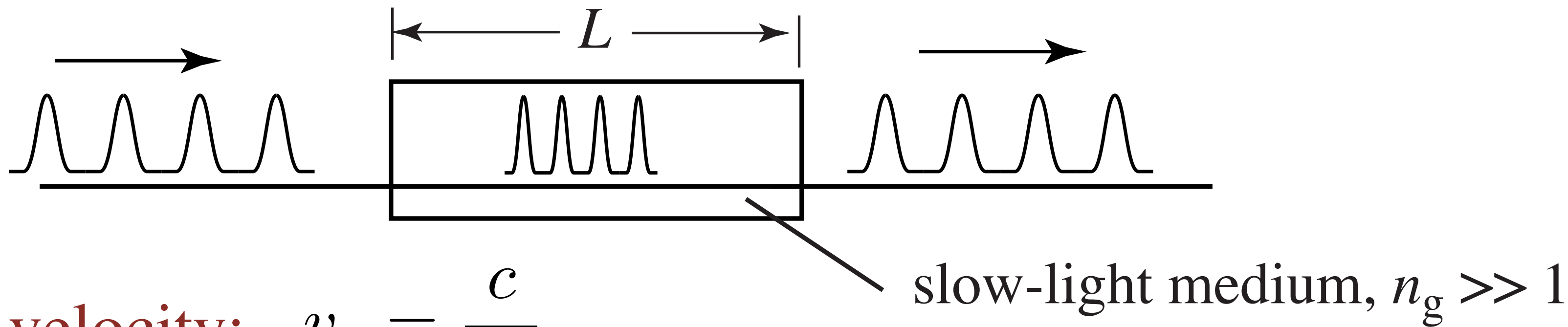
Key figure of merit:
normalized time delay = total time delay / input pulse duration
$\approx$ information storage capacity of medium

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

But data packets used in telecommunications contain $\approx 10^3$ bits

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

Review of Slow-Light Fundamentals



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

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

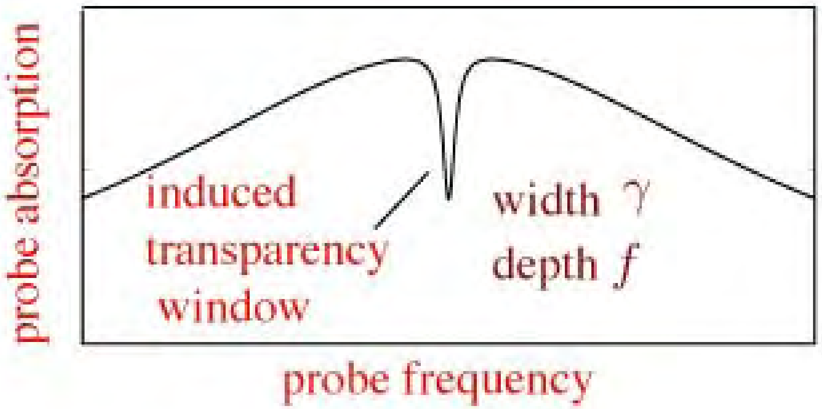
group delay: $T_g = \dfrac{L}{v_g} = \dfrac{L n_g}{c}$

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

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

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

normalized induced delay (T_0 = pulse width)

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

Limitations to Time Delay

Normalized induced delay

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

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

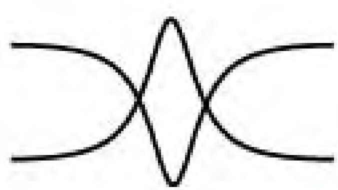
There will thus be a range of time delays, leading to a range of delays and pulse spreading

Insist that pulse not spread by more than a factor of 2. Thus

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

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

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

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

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

  which has no upper bound.

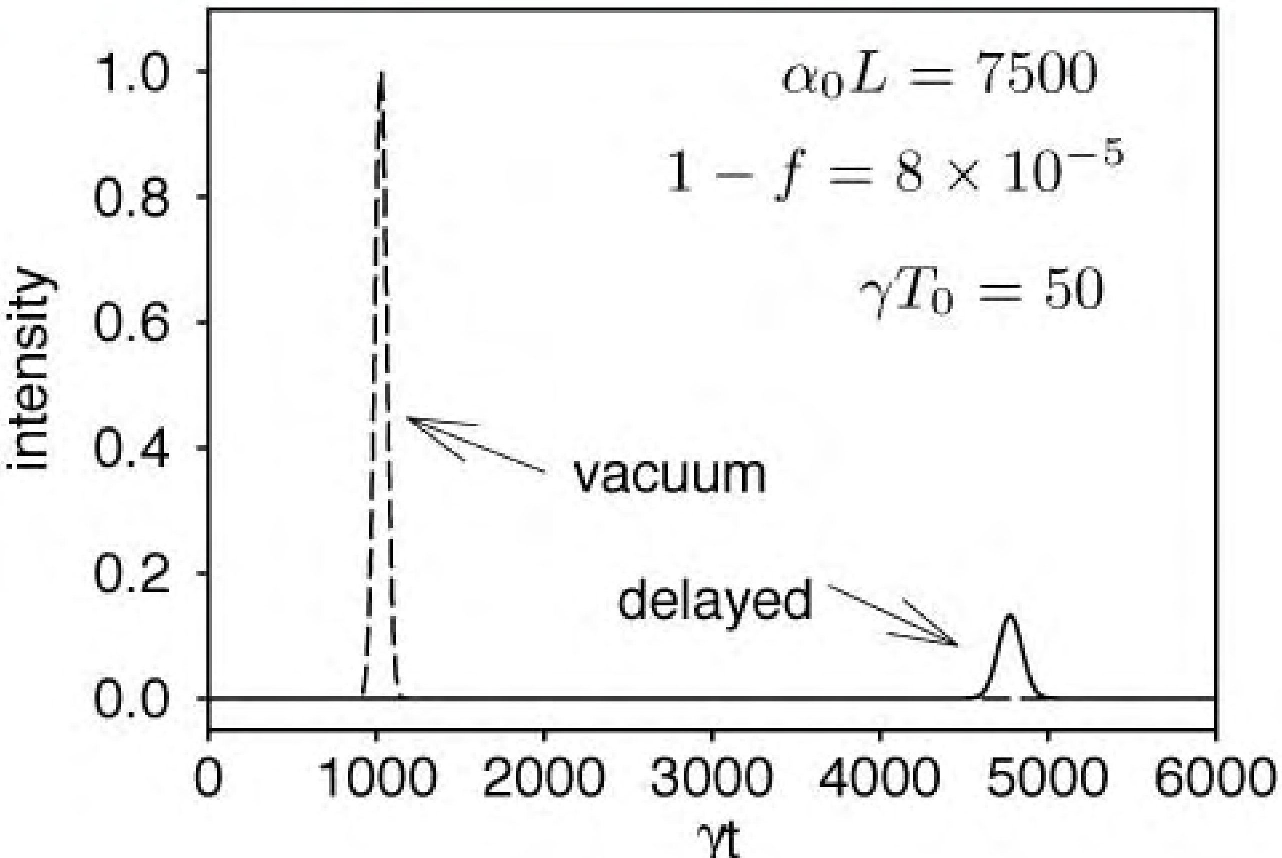
- But to achieve this time delay, one needs a large initial (before saturation) optical depth given by

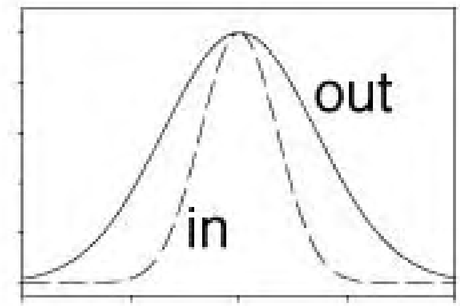
$$\alpha_0 L = (4/3)(T_{\mathrm{del}}/T_0)^2_{\max}.$$

- 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

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

Numerical Example Showing Large Relative Delay

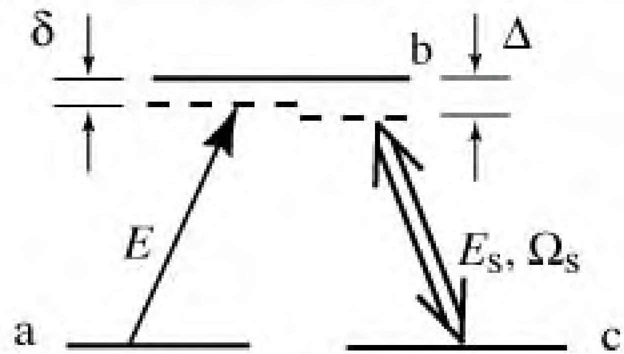




Factor-of-two pulse spreading

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

Specific Example: Electromagnetically Induced Transparency



- The reponse to the probe field in the presence of the strong coupling field is given by

$$\chi^{(1)} = -\frac{\alpha_0 c}{\omega} \frac{[i(\delta - \Delta) - \gamma_{ca}]}{(i\delta - \gamma_{ba})[i(\delta - \Delta) - \gamma_{ca}] + |\Omega_s/2|^2}$$

- The width of the transparency window displays power broadening: $\gamma = \frac{|\Omega_s/2|^2}{\gamma_{ba}}$

- The residual absorption can be rendered arbitrarily small ($f \rightarrow 1$) through use of an intense coupling field.

$$f = \frac{|\Omega_s/2|^2}{\gamma_{ca}\gamma_{ba} + |\Omega_s/2|^2}$$

- For ($f \rightarrow 1$) the normalized delay can be arbitrarily large

$$\left(\frac{T_{del}}{T_o}\right)_{\max} = \frac{3}{2} \frac{|\Omega_s/2|^2 T_o}{\gamma_{ba}}.$$

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.

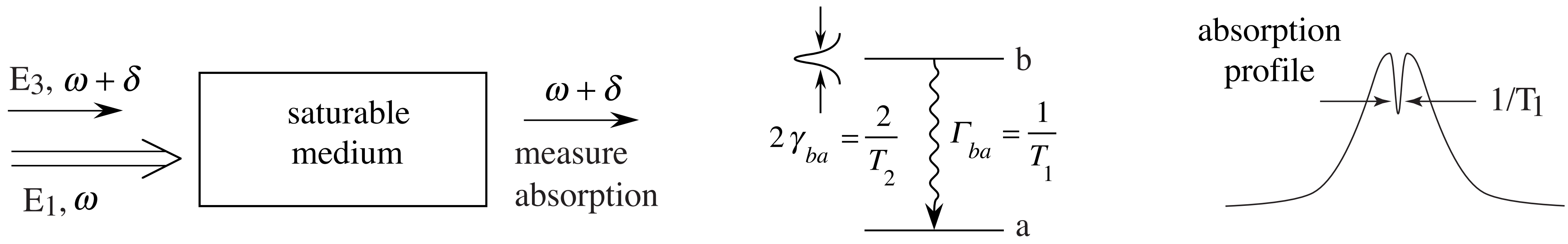
Another recent study [2] reaches a more pessimistic (although entirely mathematically consistent) conclusion by stressing the severity of residual absorption, especially in the presence of Doppler broadening.

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.

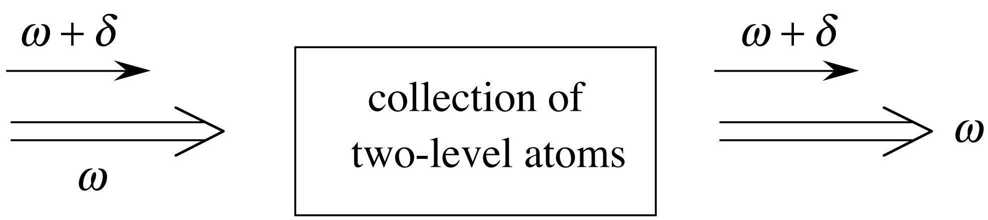
Slow Light via Coherent Population Oscillations

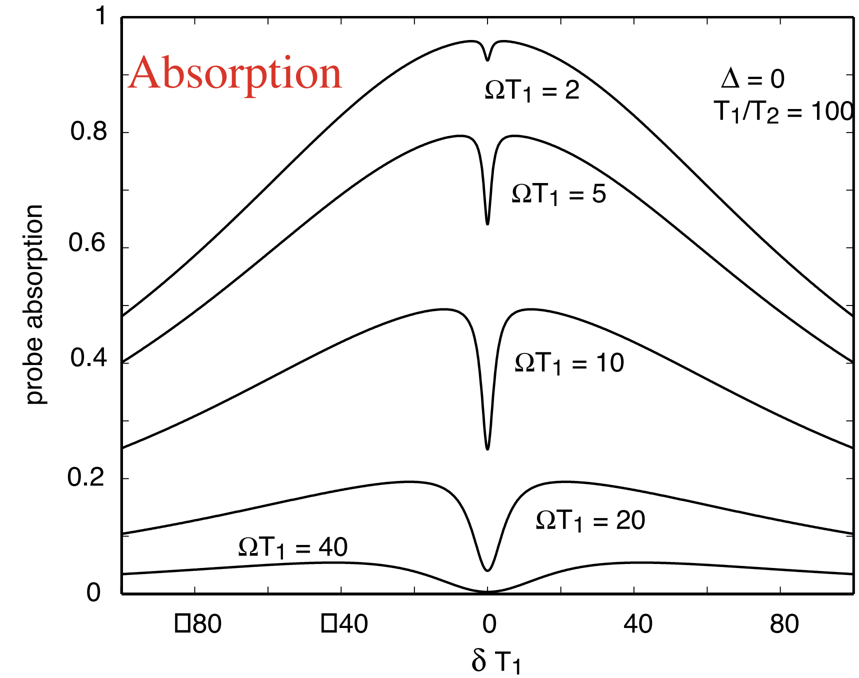


- Ground state population oscillates at beat frequency δ (for $\delta < 1/T_1$).
- Population oscillations lead to decreased probe absorption (by explicit calculation), even though broadening is homogeneous.
- Rapid spectral variation of refractive index associated with spectral hole leads to large group 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!

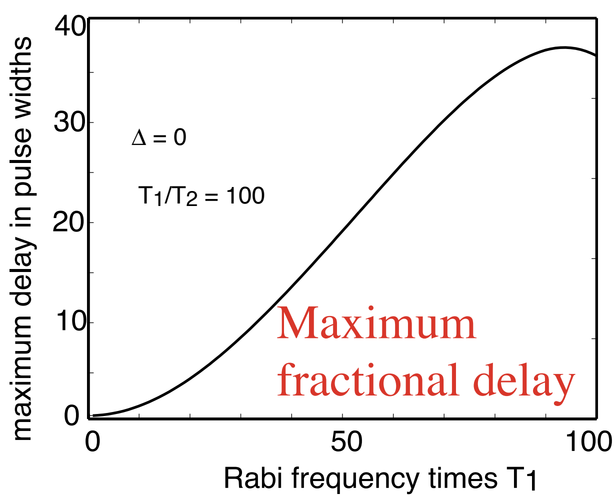
PRL 90,113903(2003); Science, 301, 200 (2003)

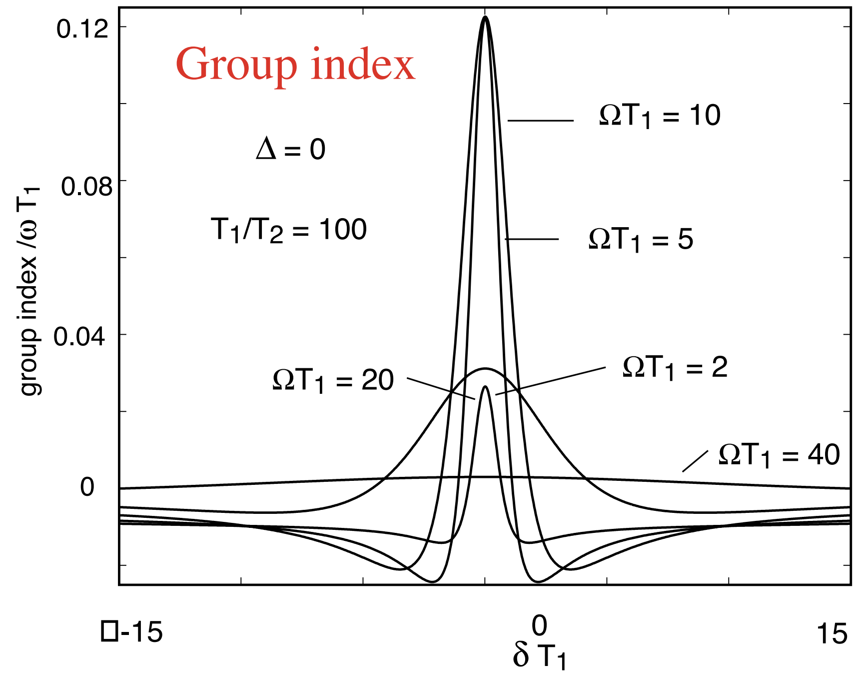
Prospects for Large Fractional Delays Using CPO





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





Boyd et al., Laser Physics 2005.

Summary

There are no *fundamental* limitations to the maximum normalized pulse delay.

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

To achieve a longer fractional delay saturate deeper to propagate farther

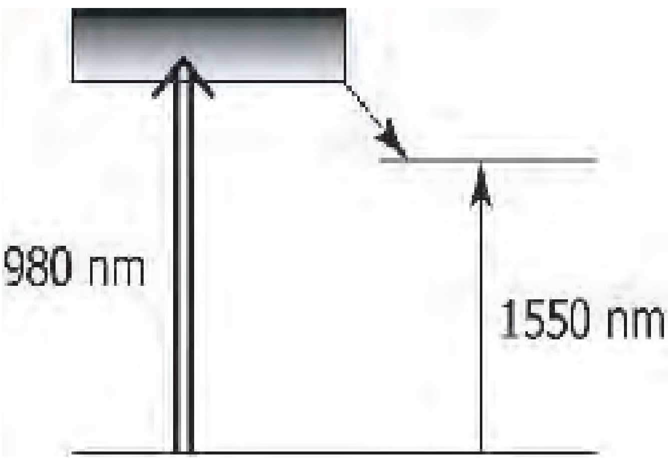
Exciting possibilities exist for optical buffering and other photonics applications if normalized time delays in the range of 10 – 1000 can be achieved.

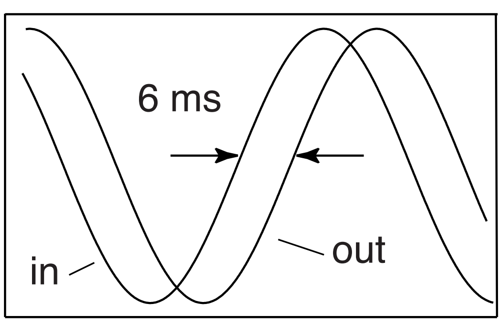
Next: Find material with faster response (semiconductors?) (to allow delay of shorter pulses)

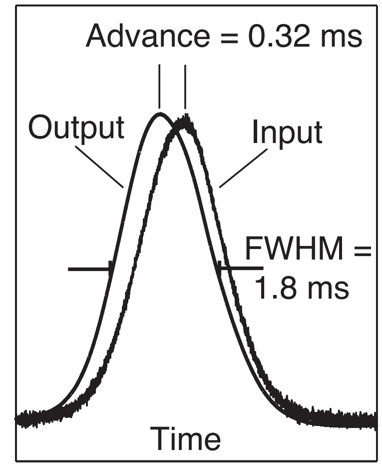
Some New Results

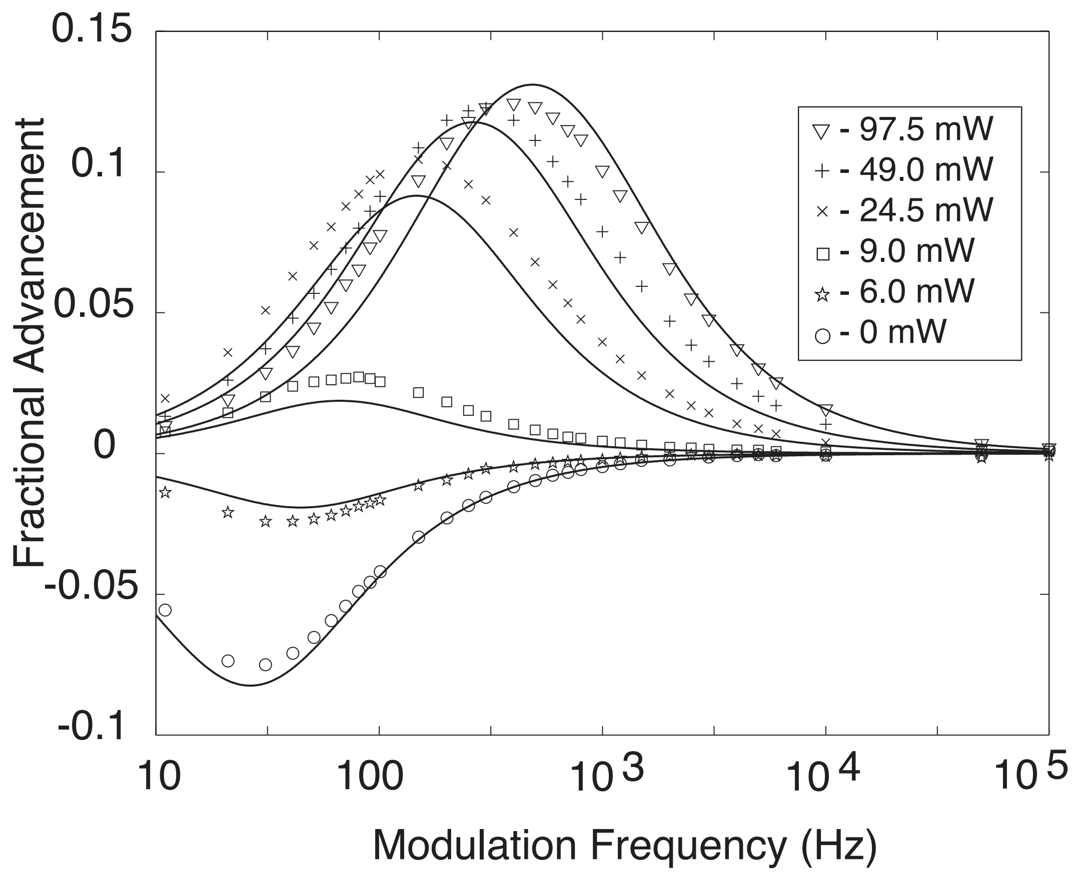
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



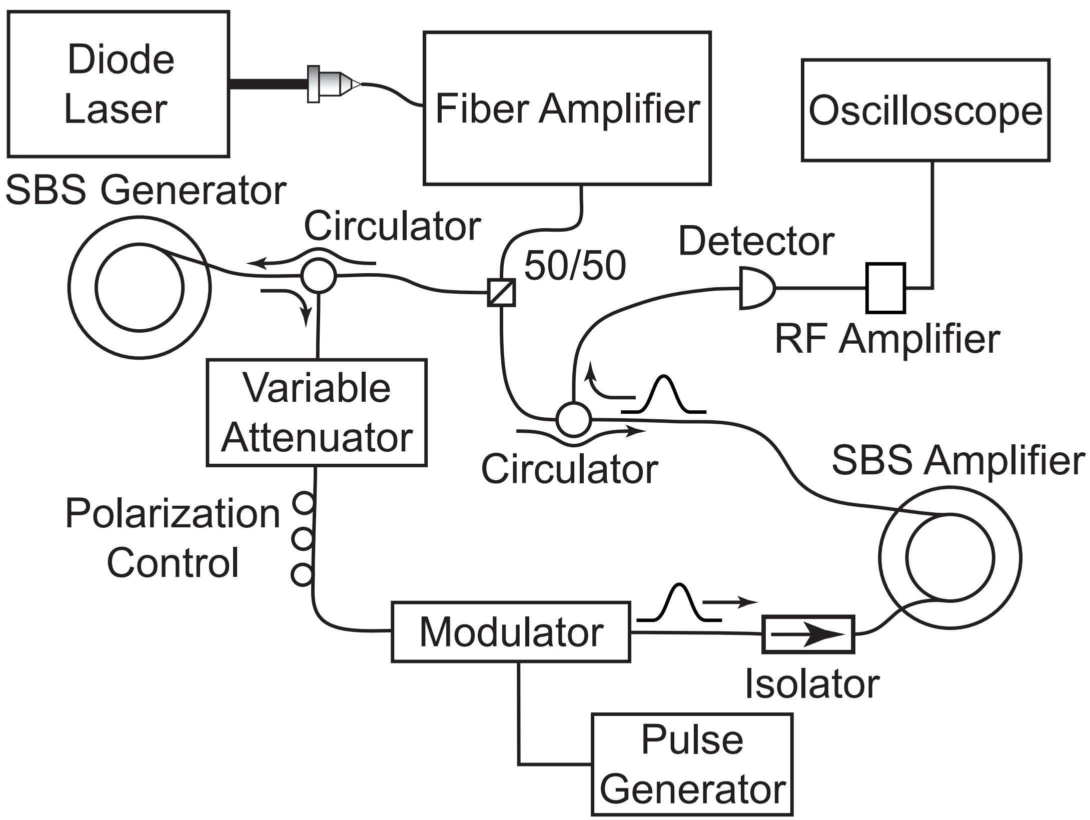




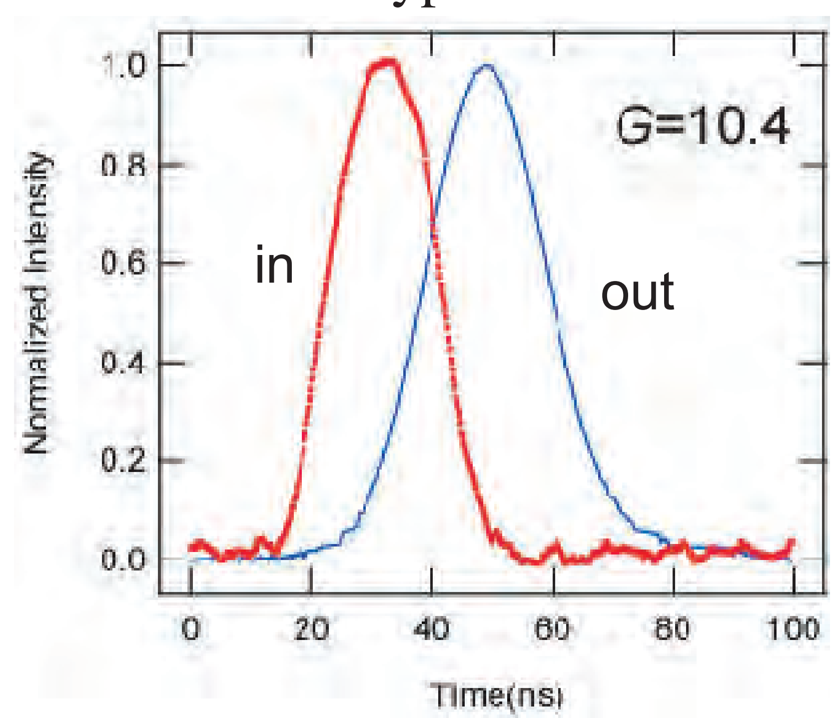


Slow-Light via Stimulated Brillouin Scattering

- Rapid spectral variation of the refractive response associated with SBS gain leads to slow light propagation
- Supports bandwidth of 100 MHz, group index of about 100
- Even faster modulation for SRS
- Joint project with Gaeta and Gauthier



typical data



PRL 94, 153902 (2005).

Thank you for your attention.

And thanks to NSF and DARPA for financial support!