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

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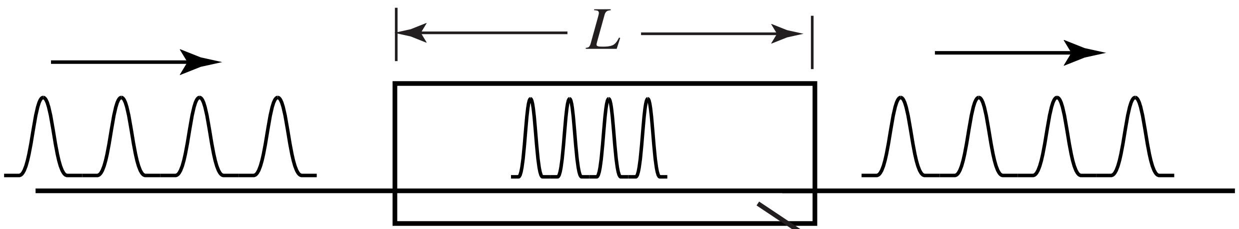
with Aaron Schweinsberg, Petros Zerom, Giovanno Piredda,
Zhimin Shi, Heedeuk Shin, and others

Presented OFC, March 7, 2006.

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
$\approx$ information storage capacity of medium

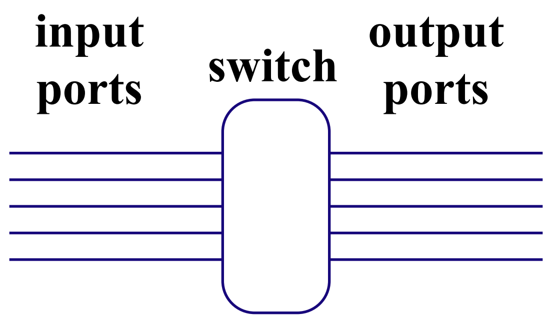
Best result to date: delay by 4 pulse lengths (Kasapi et al. 1995)

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

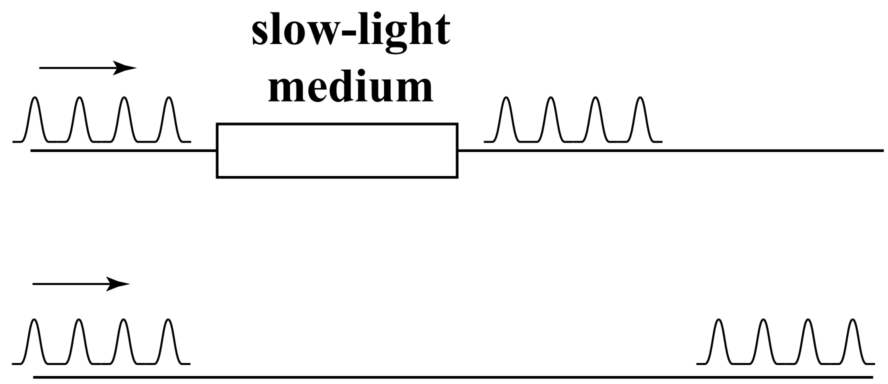
What are the prospects for obtaining slow-light delay lines with 10^3 bits capacity?

Slow Light and Optical Buffers

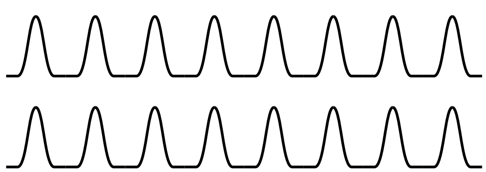
All-Optical Switch



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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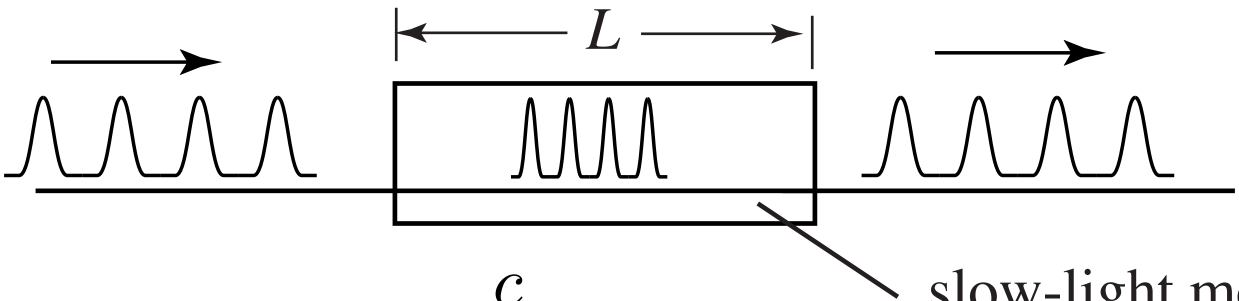

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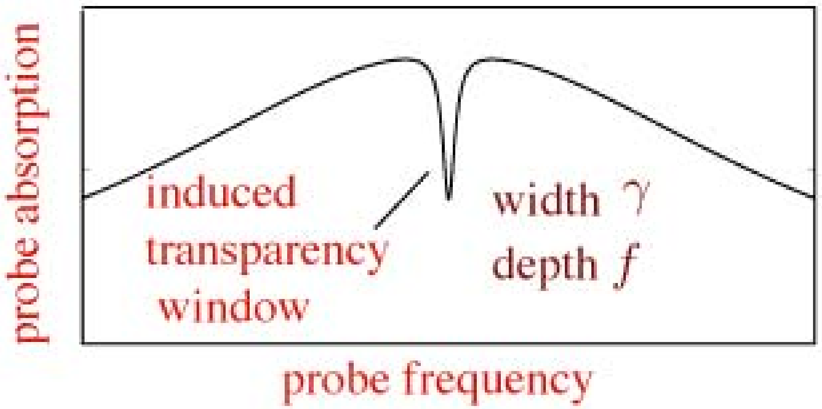
Generic Model of EIT and CPO Slow-Light Systems



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

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

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

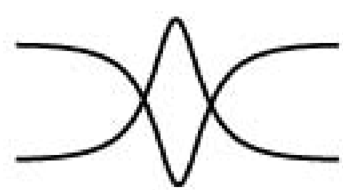
There will thus be a range of time delays, leading to a range of delays and pulse spreading

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

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

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

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

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.

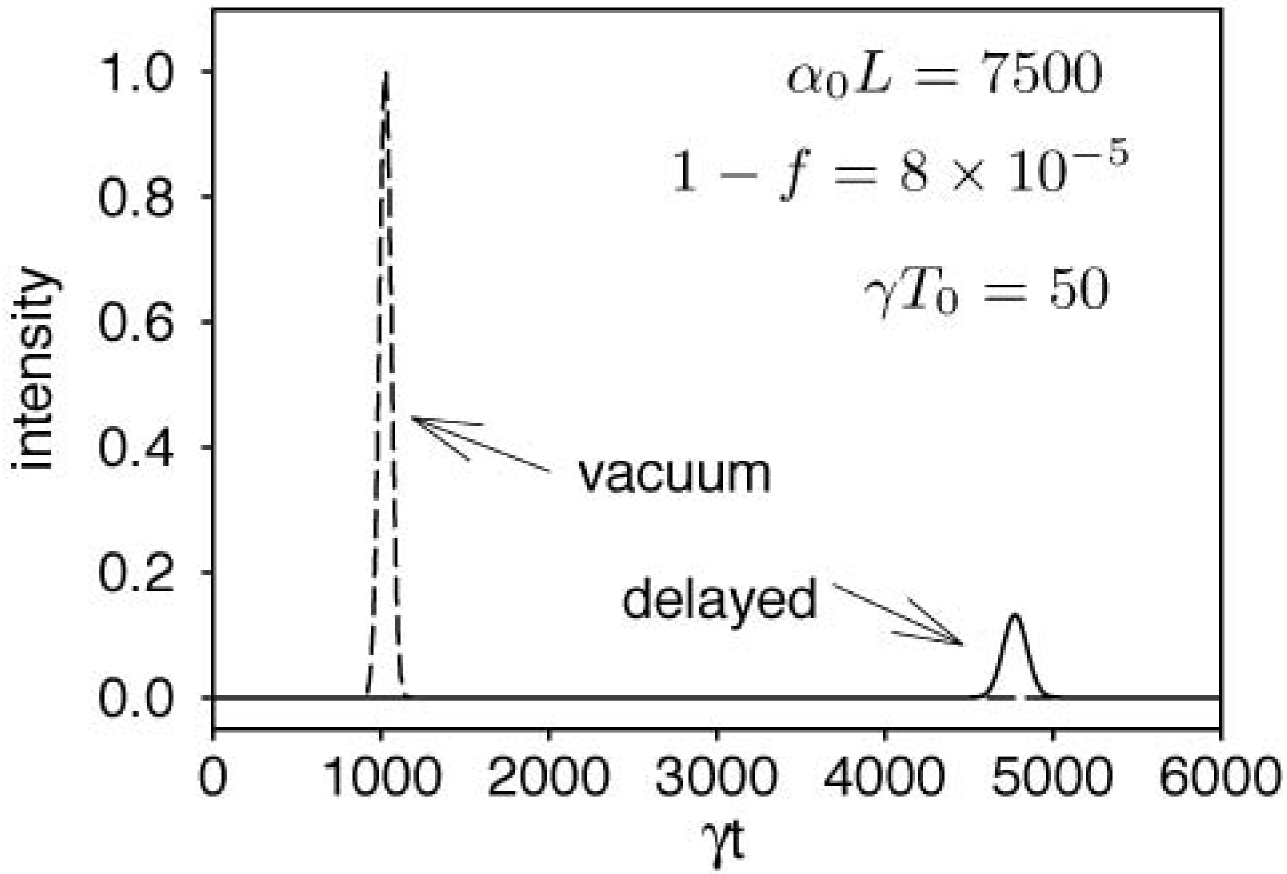
- But to achieve this time delay, one needs a large initial (before saturation) optical depth given by

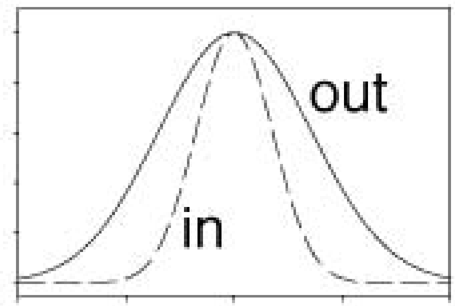
$$\alpha_0 L = (4/3)(T_{\mathrm{del}}/T_0)^2_{\mathrm{max}}.$$

- 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 $T_{\rm del}/T_0 = 75.$

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.

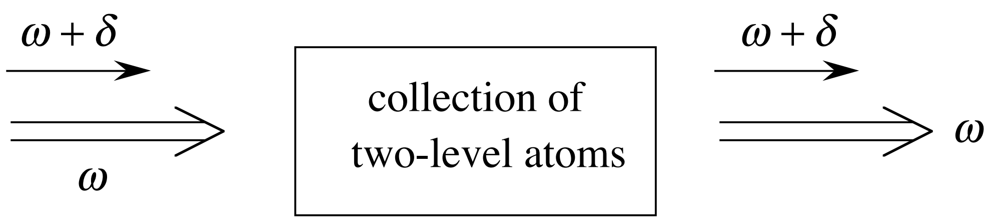
Another recent study [2] reaches a more pessimistic (although entirely mathematically consistent) conclusion by stressing the severity of residual absorption, especially in the presence of Doppler broadening.

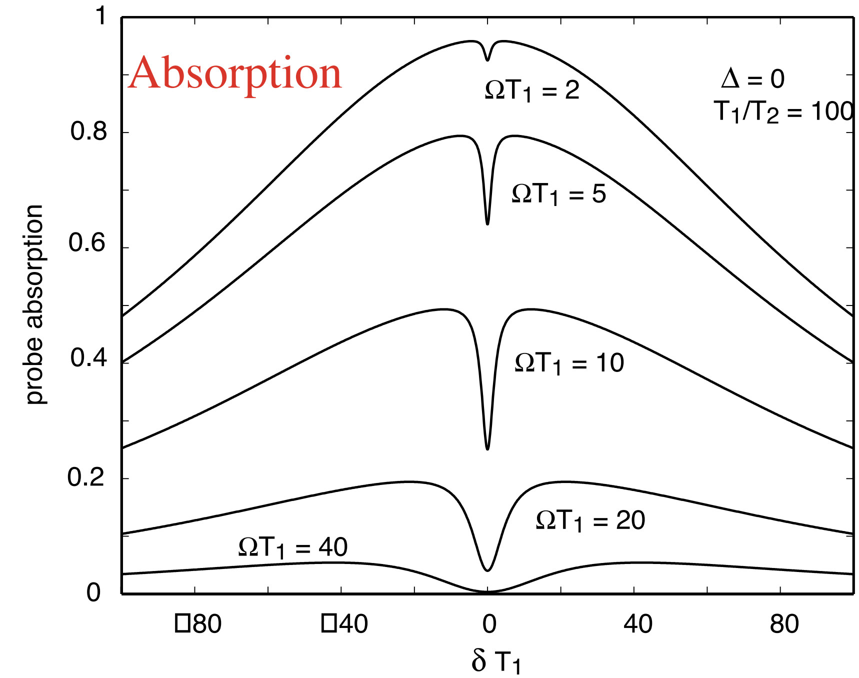
Our challenge is to minimize residual absorption.

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

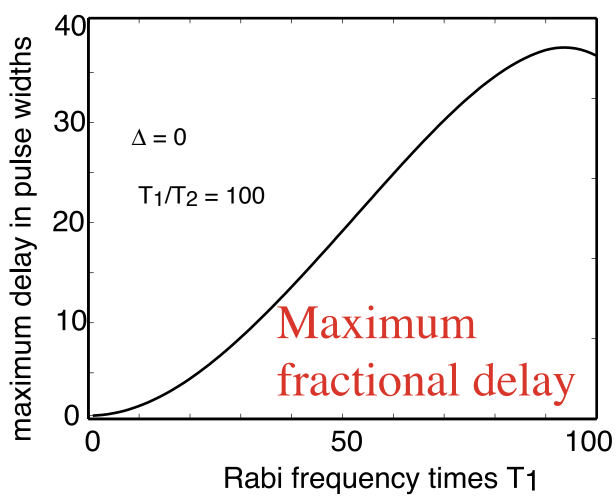
[2] Matsko, Strekalov, and Maleki, Opt. Express 13, 2210, 2005.

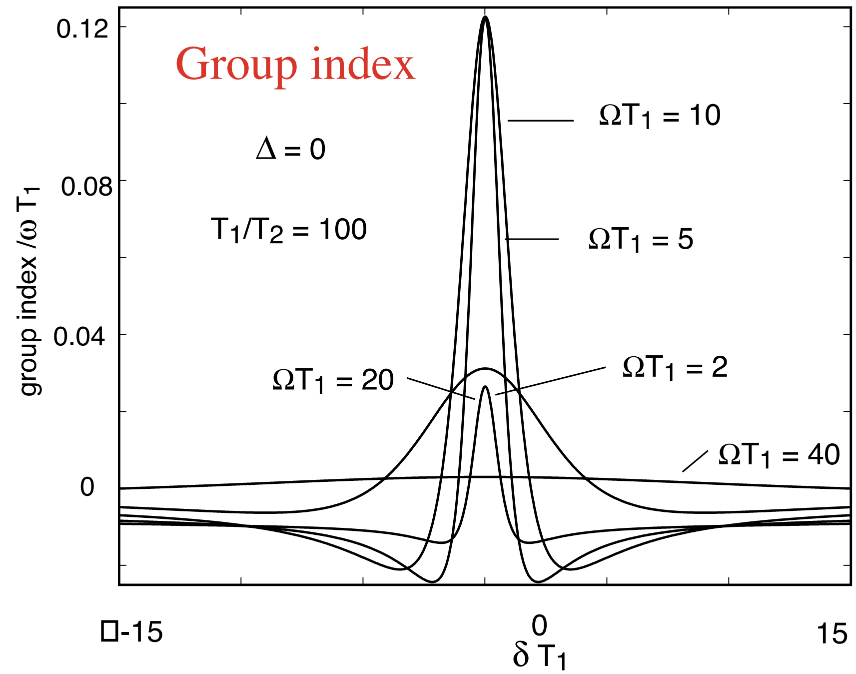
Prospects for Large Fractional Delays Using CPO





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





Boyd et al., Laser Physics 2005.

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Our Approach

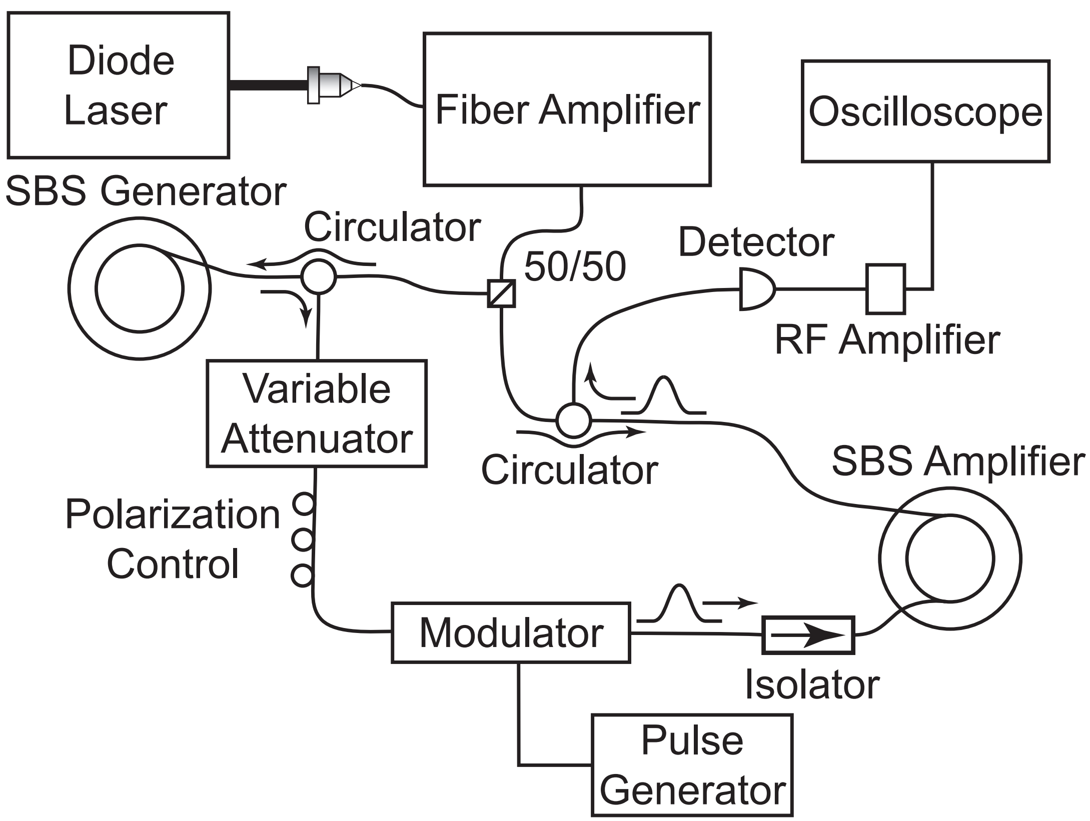
Slow light in a room-temperature solid-state material.

Systems under investigation:

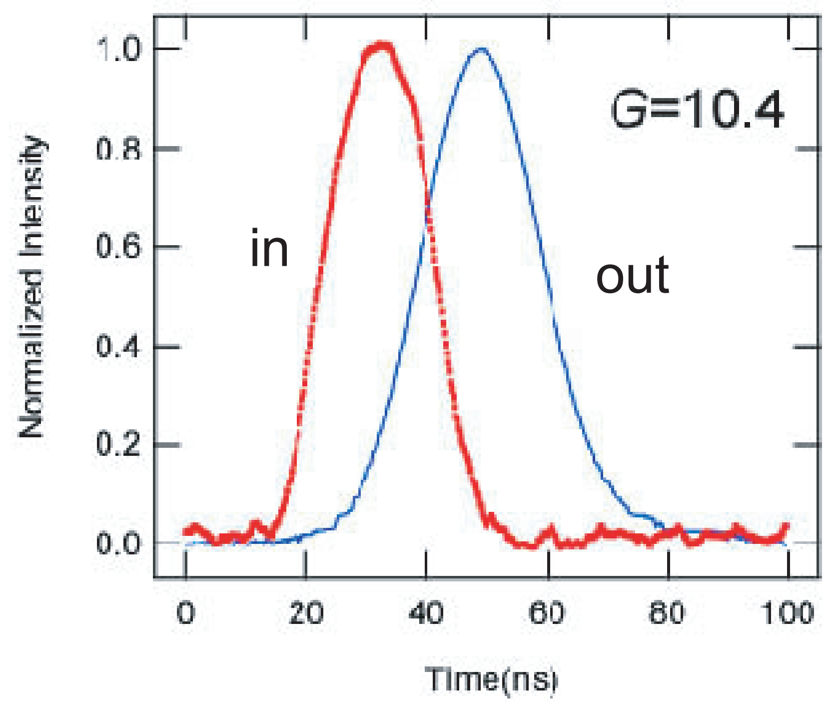
1. Stimulated Brillouin Scattering
2. Stimulated Raman Scattering
3. Wavelength Conversion and Dispersion
4. Coherent Population Oscillations
    a. Ruby and alexandrite
    b. Semiconductor quantum dots (PbS)
    c. Semiconductor optical amplifier
    d. Erbium-doped fiber amplifier

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

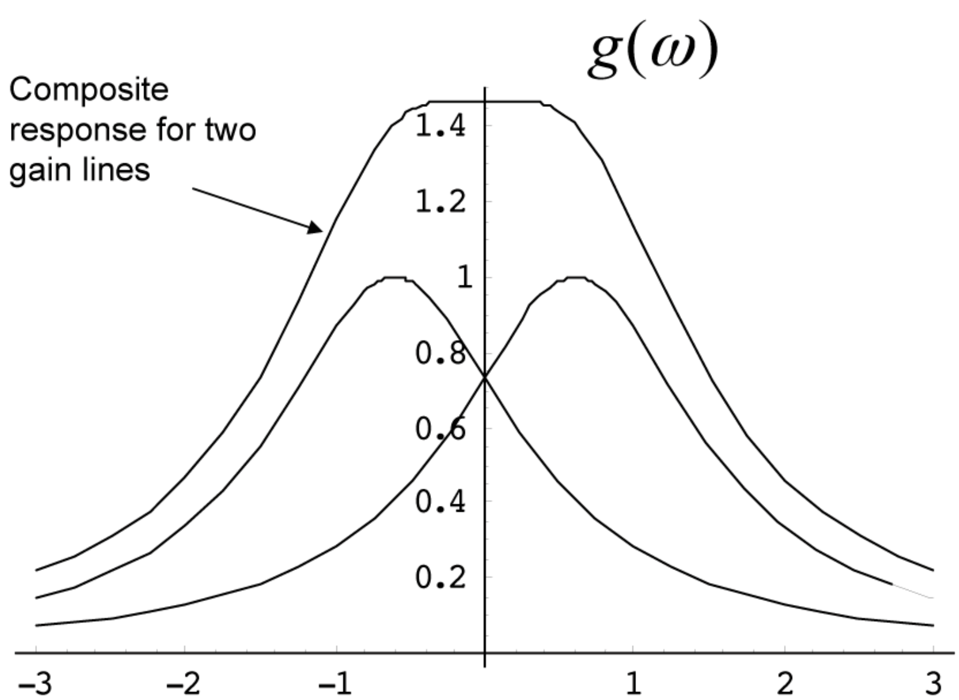


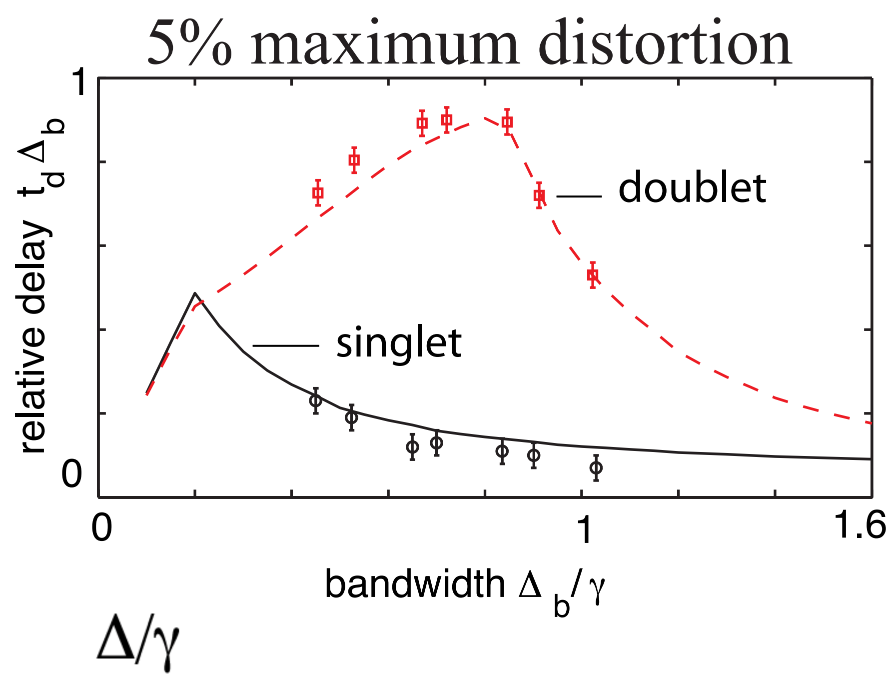
typical data



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).

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

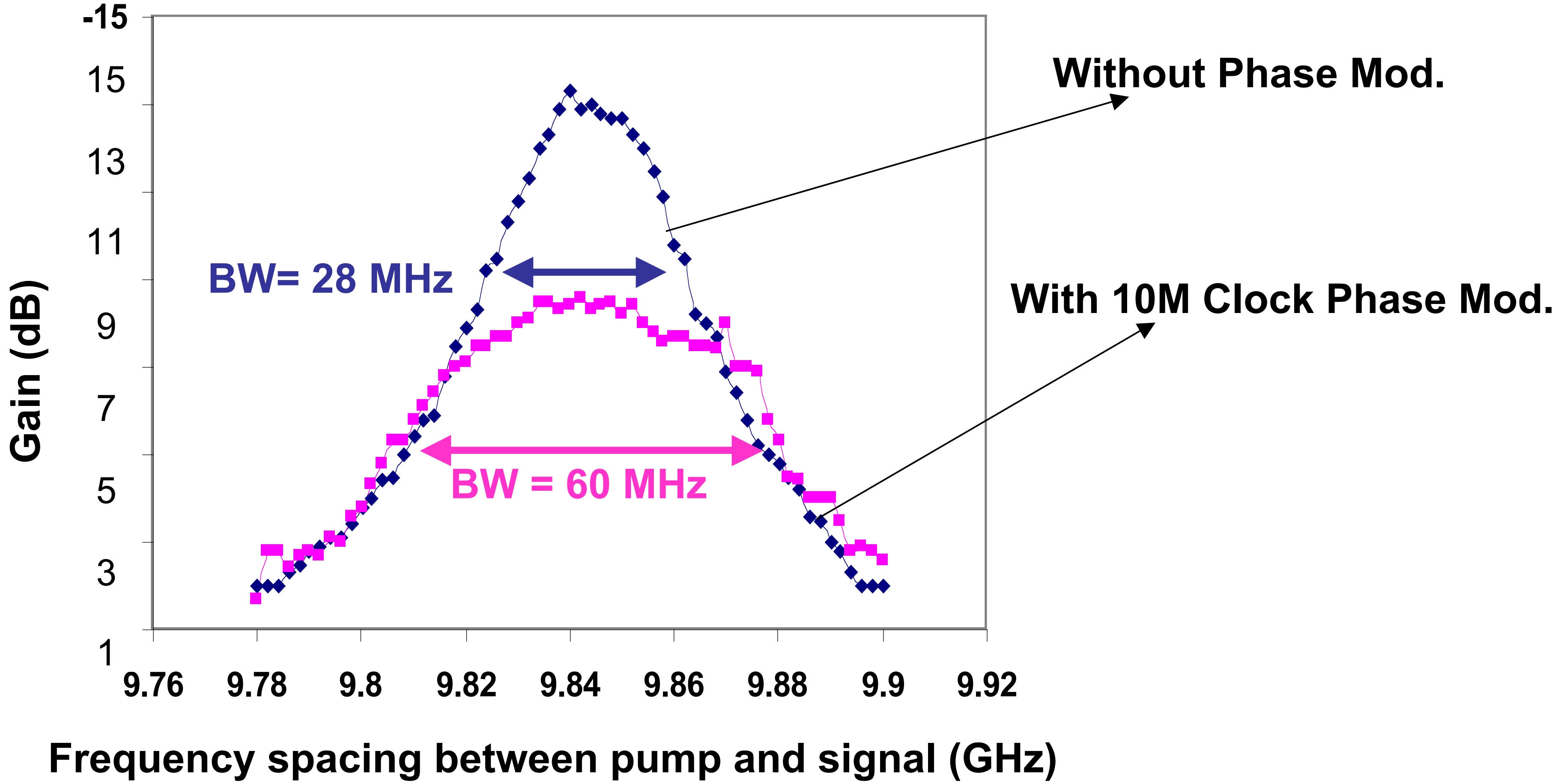




Stenner et al., Opt. Express 13 9995 (2005)

Study of SBS Gain Spectrum Broadening

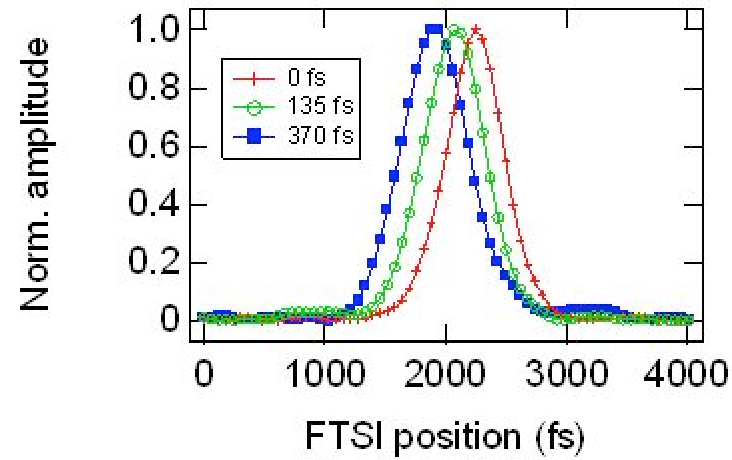
Expand the BW by phase modulating the pump

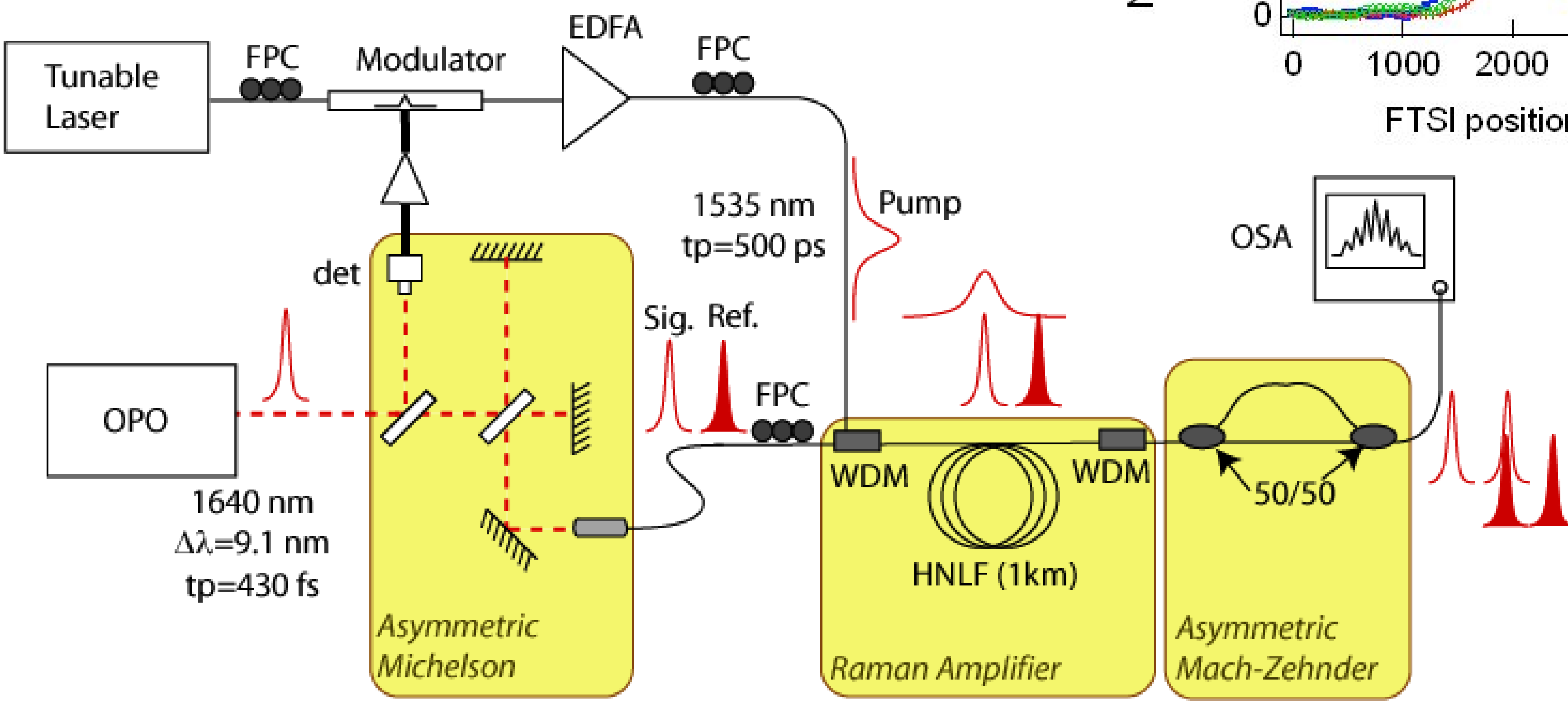


- Gain BW: 28 MHz → 60 MHz (10 MHz clock phase modulating the pump)

Slow-Light by Stimulated Raman Scattering

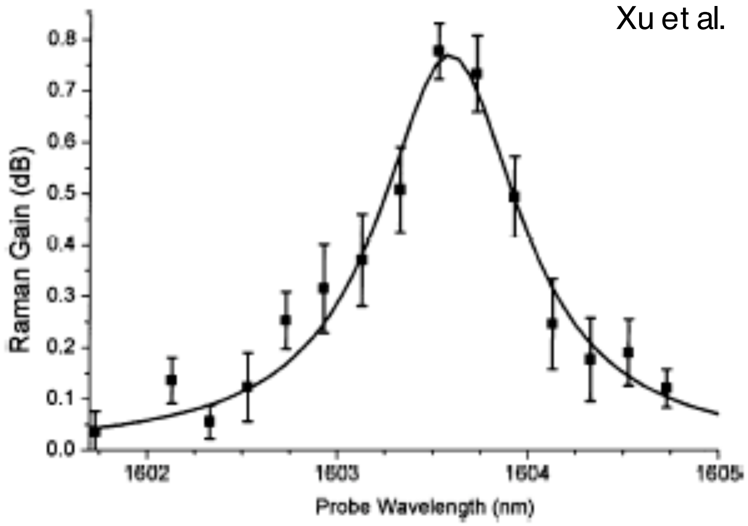
- The Raman linewidth (~3 THz) is adequate for foreseeable applications
- 370 fs delay observed for 430 fs input pulse (85% of pulse width)
- Alex Gaeta, Cornell



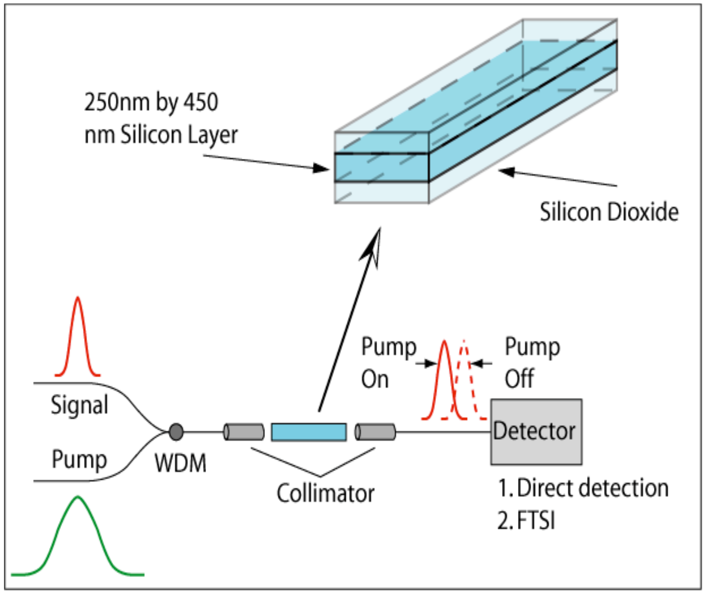


Slow Light Using SRS in a Silicon Nanostructure

- 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)].



Xu et al.

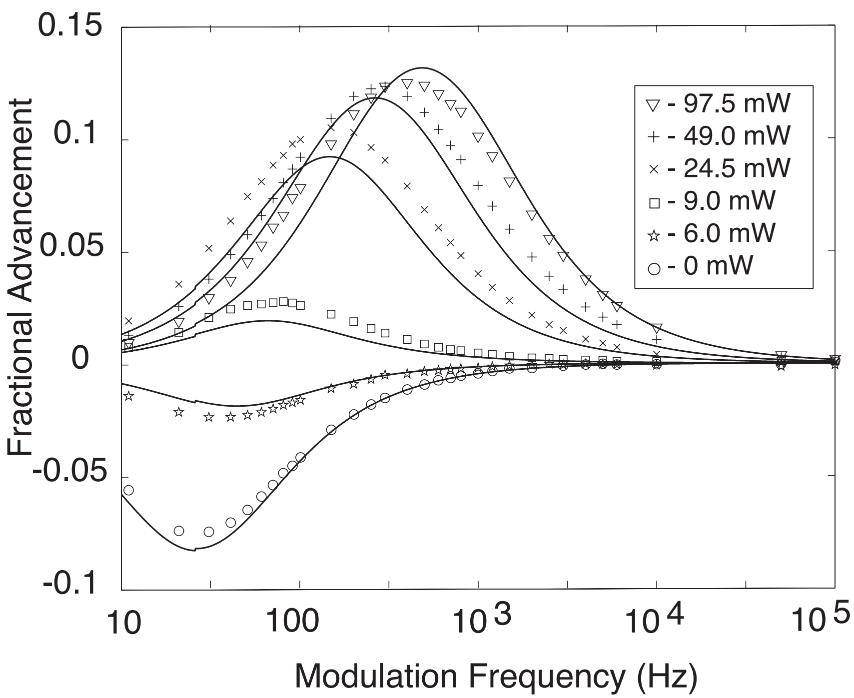


- System allows for flexibility in the operating wavelength (> 1 μm).
- Planar waveguide allows for CMOS-compatible all-optical tunable delay.

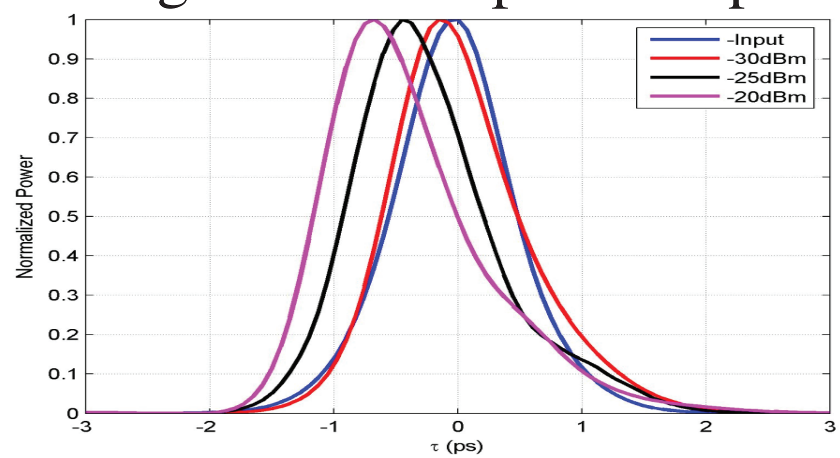
Slow Light via Coherent Population Oscillations

- 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.

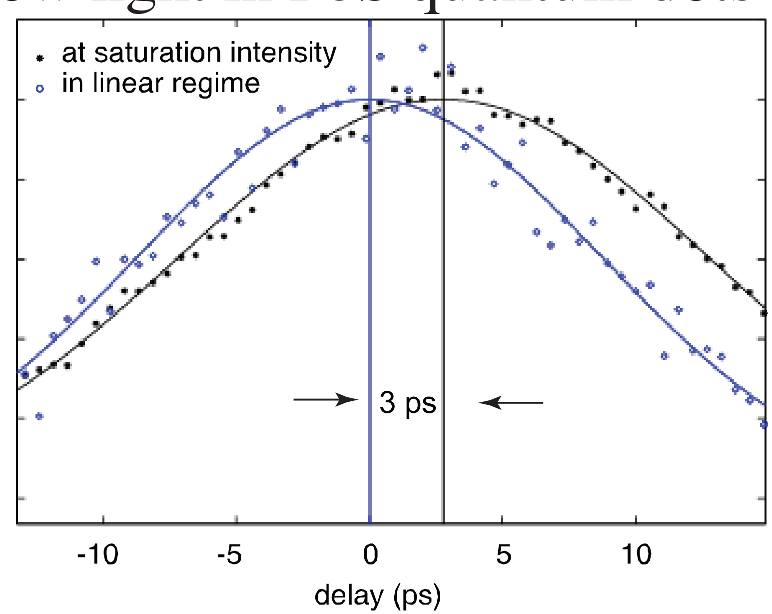
- Slow and fast light in an EDFA



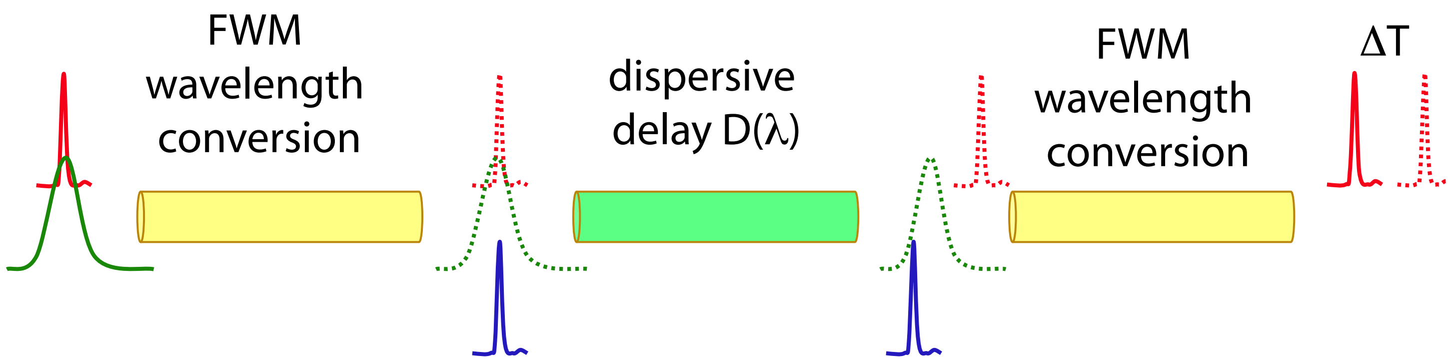
- Slow light in a SC optical amplifier



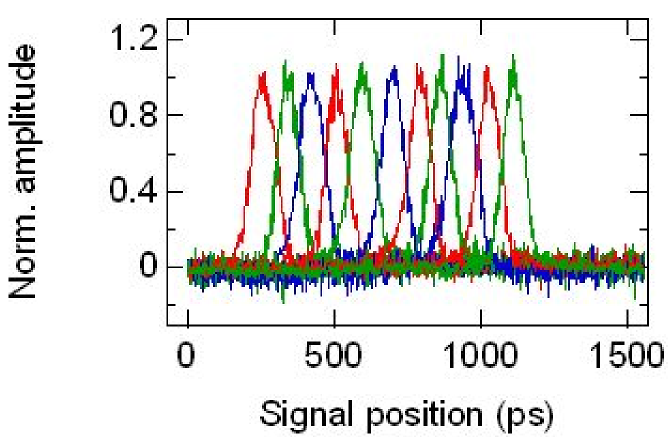
- Slow light in PbS quantum dots

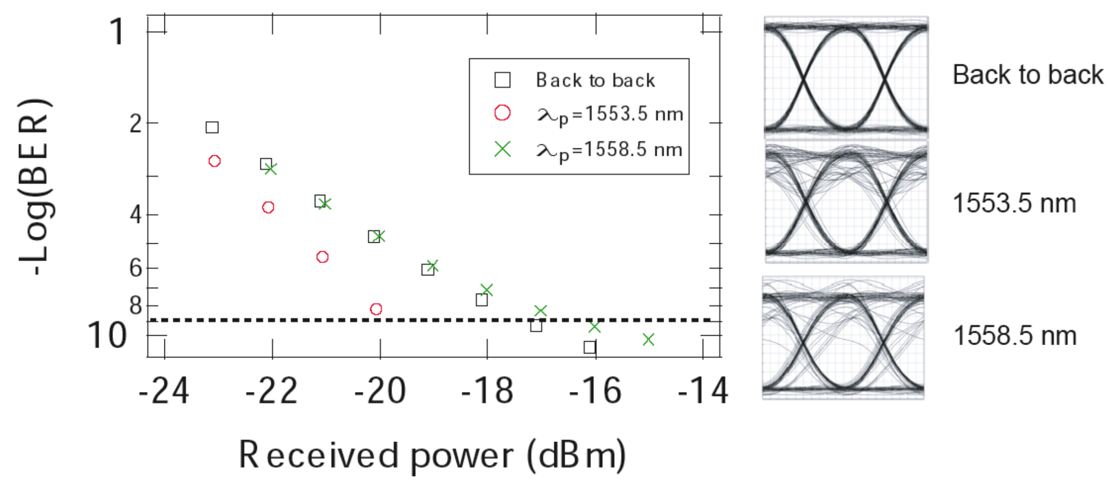


FWM-Dispersion Delay Method



- 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





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Interest in Slow Light

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

Fundamentals of optical physics

Optical delay lines, optical storage, optical memories

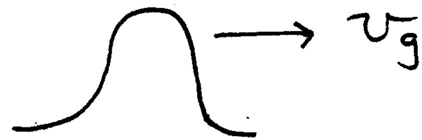
Implications for quantum information

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

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

Group Velocity

Pulse
(wave packet)



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

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

Thus

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

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

Switch to Overheads

Approaches to Slow Light Propagation

- Use of quantum coherence (to modify the spectral dependence of the atomic response)

  e.g., electromagnetically induced transparency

- Use of artificial materials (to modify the optical properties at the macroscopic level)

  e.g., photonic crystals (strong spectral variation of refractive index occurs near edge of photonic bandgap)

Slow Light in Atomic Vapors

Slow light propagation in atomic vapors, facilitated by quantum coherence effects, has been successfully observed by

Hau and Harris

Welch and Scully

Budker

and others

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

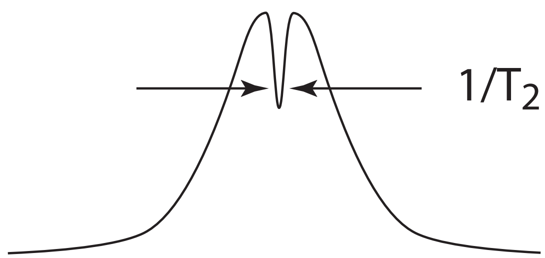
Recall that $n_g = n + \omega(dn/d\omega)$.   Need a large $dn/d\omega$.   (How?)

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

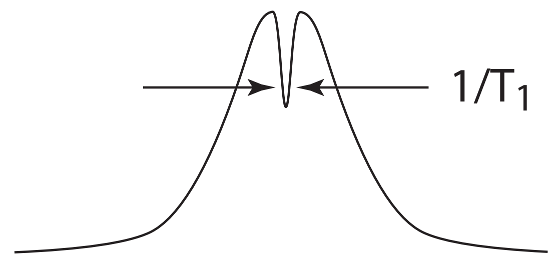
Well-known "trick" for doing so:

Make use of spectral holes due to population oscillations.

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



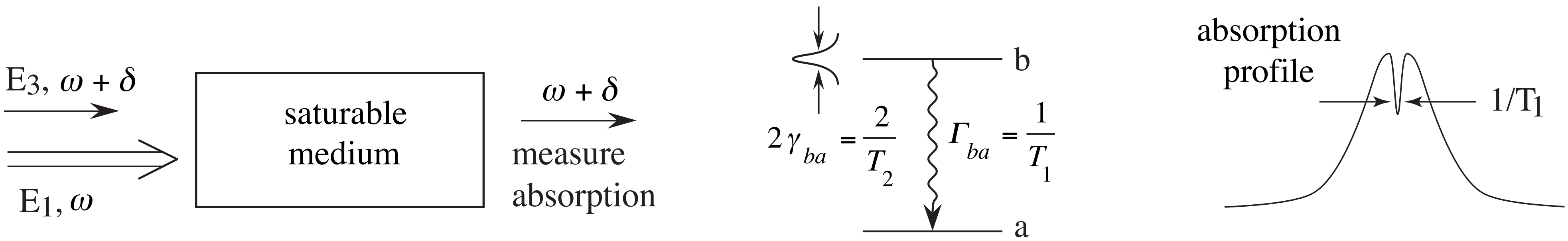
inhomogeneously broadened medium



homogeneously broadened medium (or inhomogeneously broadened)

PRL 90,113903(2003).

Slow Light via Coherent Population Oscillations

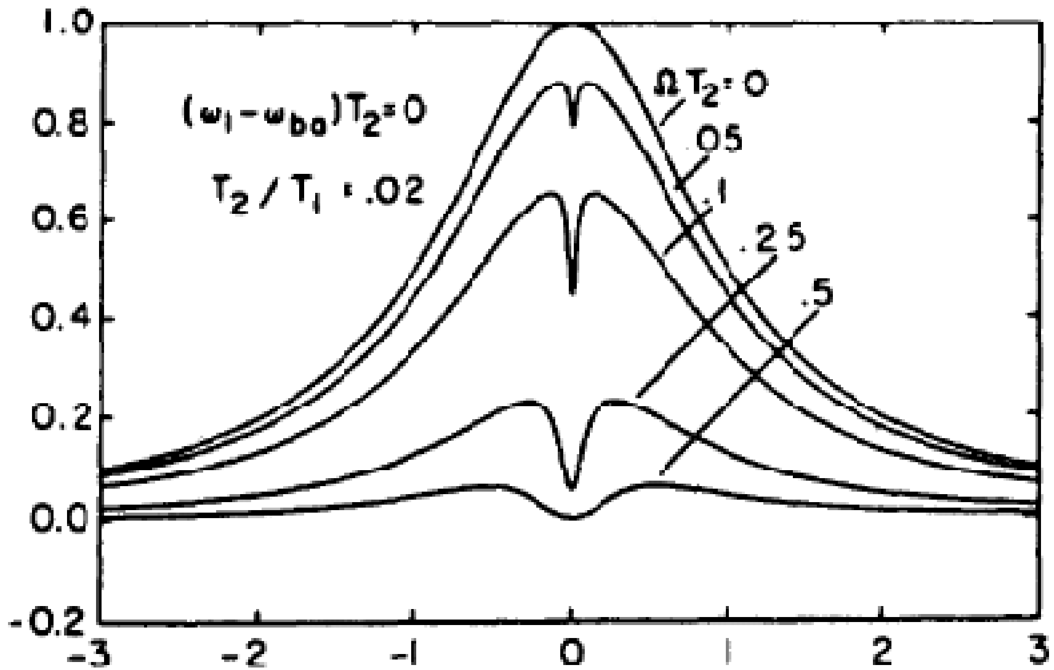


- Ground state population oscillates at beat frequency δ (for $\delta < 1/T_1$).
- Population oscillations lead to decreased probe absorption (by explicit calculation), even though broadening is homogeneous.
- Rapid spectral variation of refractive index associated with spectral hole leads to large group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

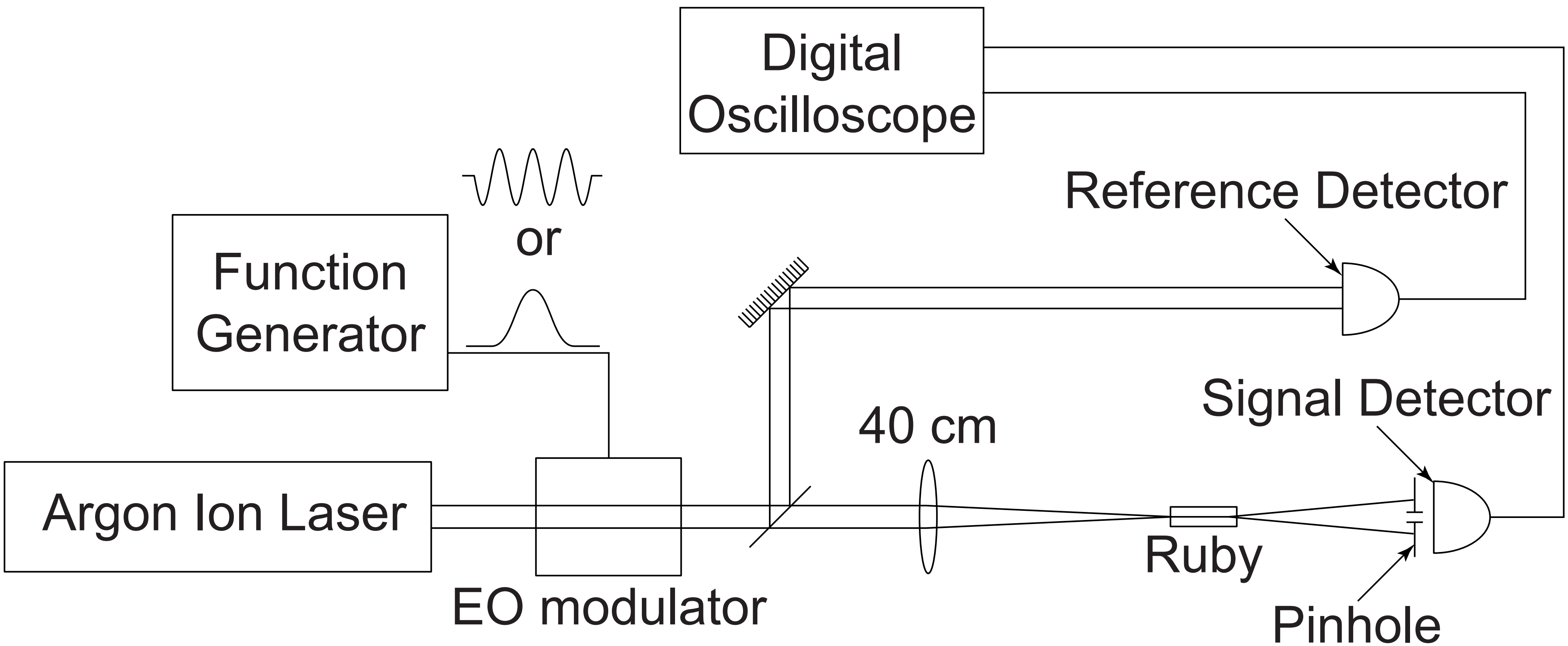
Occurs only in collisionally broadened media ($T_2 << T_1$)



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

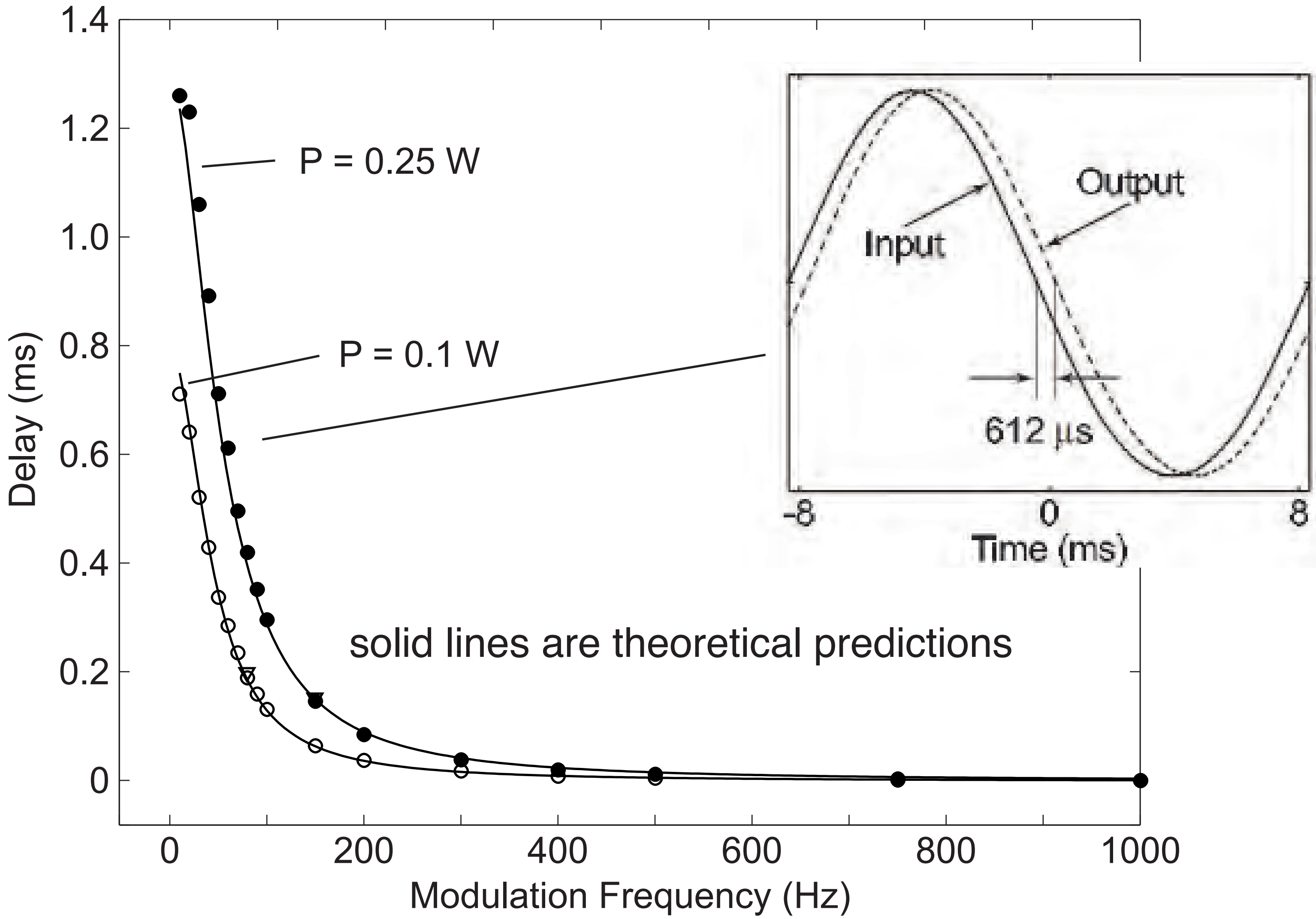
Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

Slow Light Experimental Setup



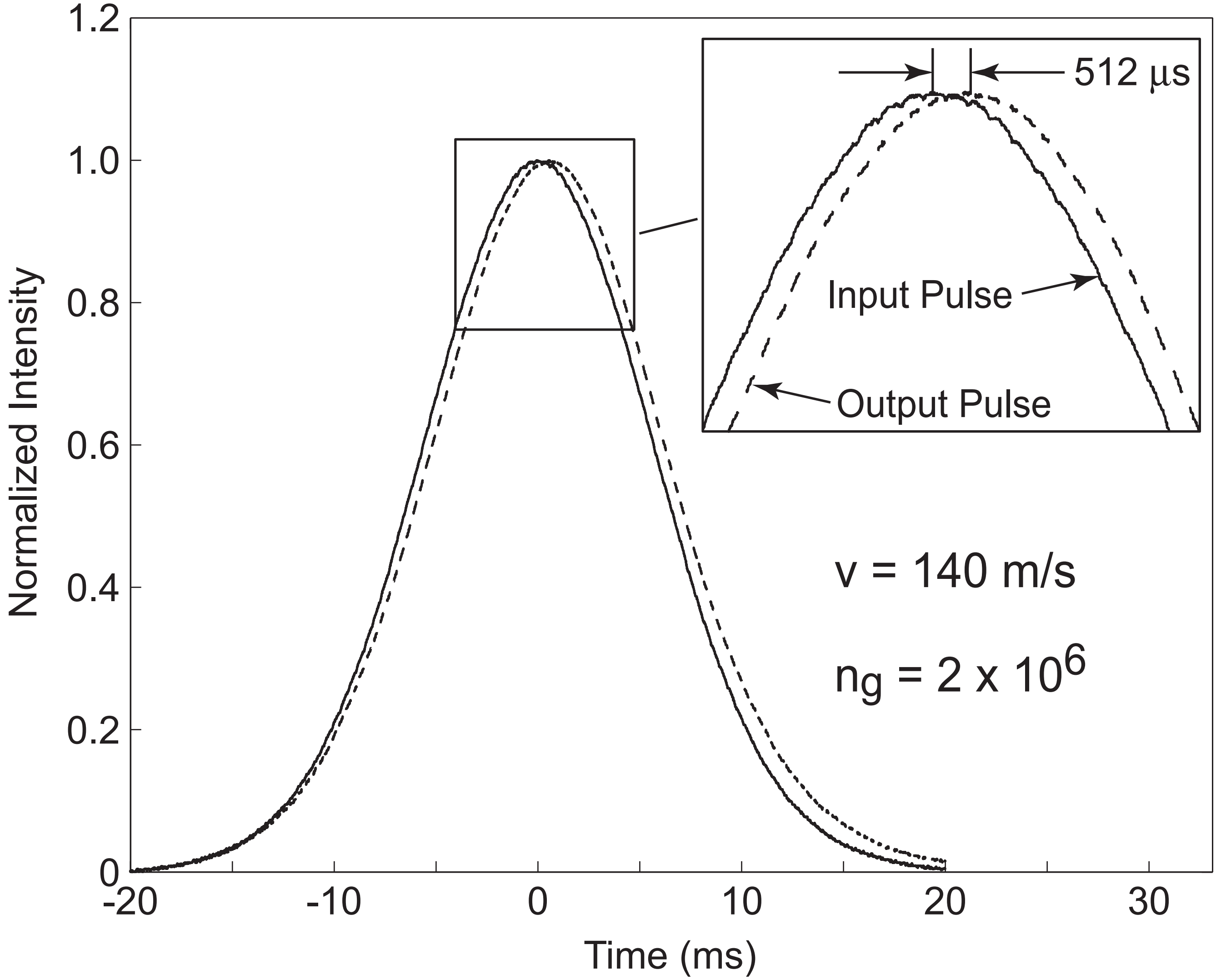
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



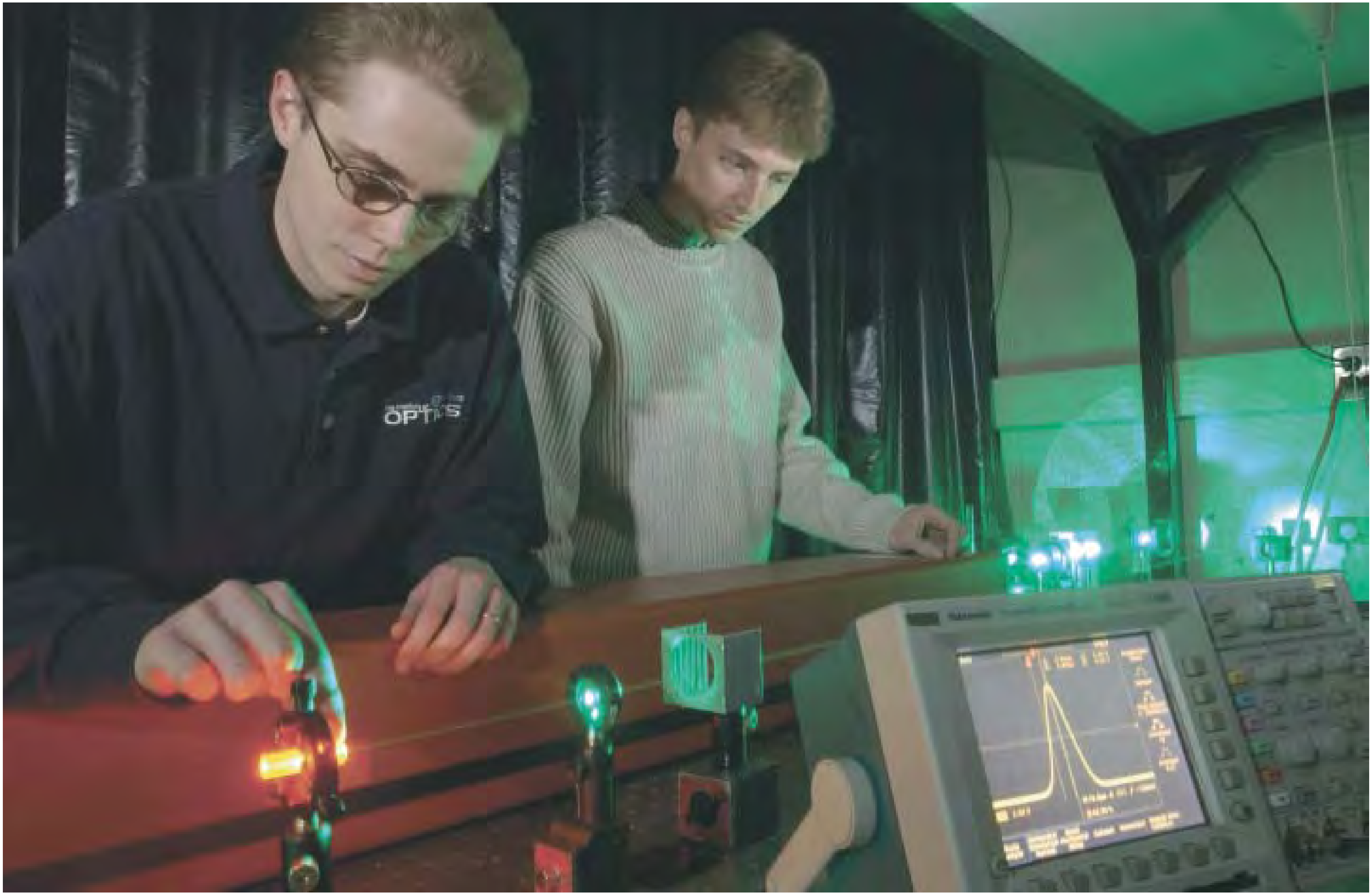
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

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

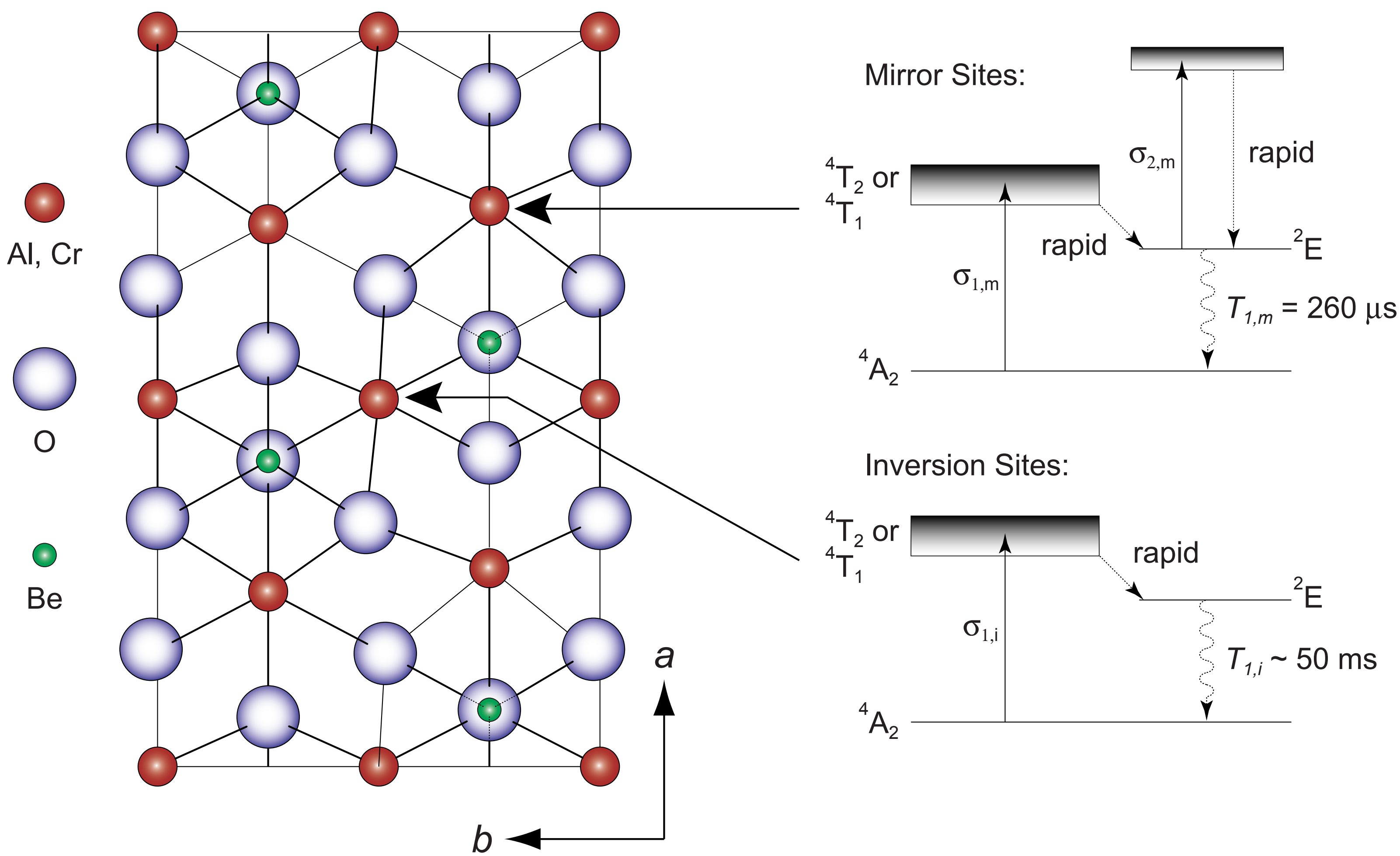
Laser need not be frequency stabilized

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

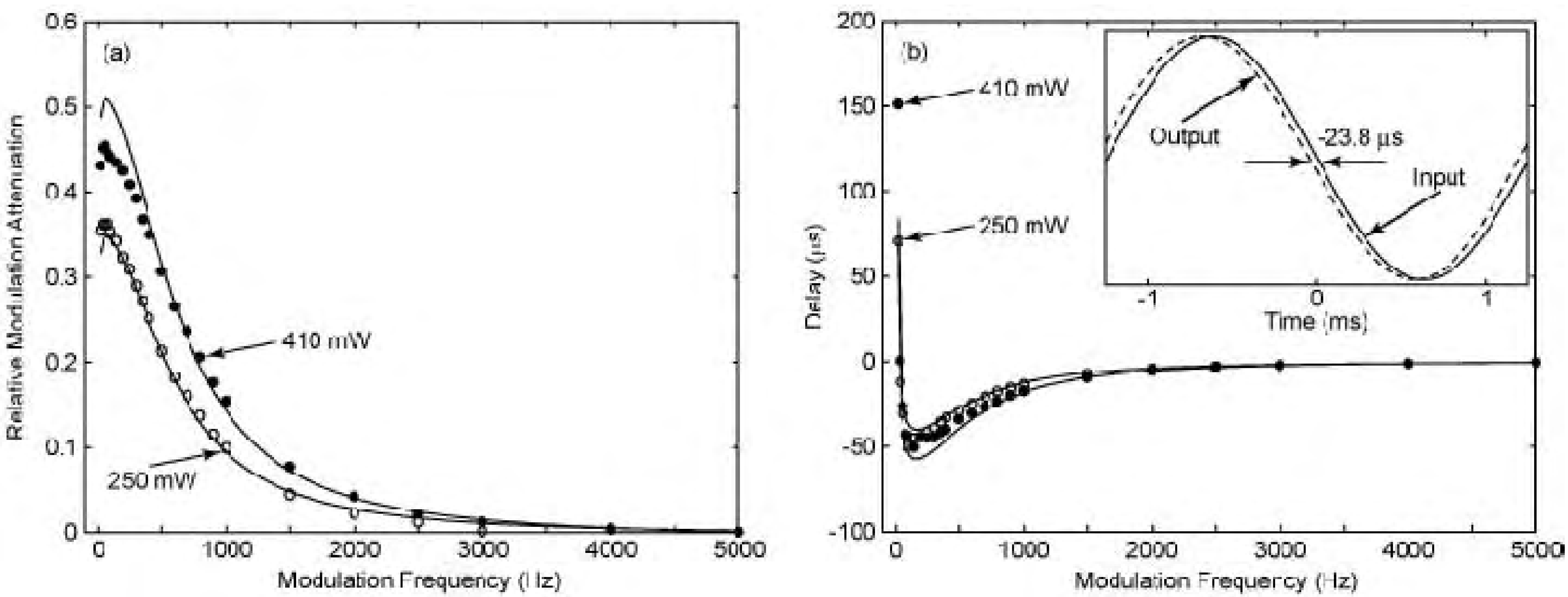


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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.

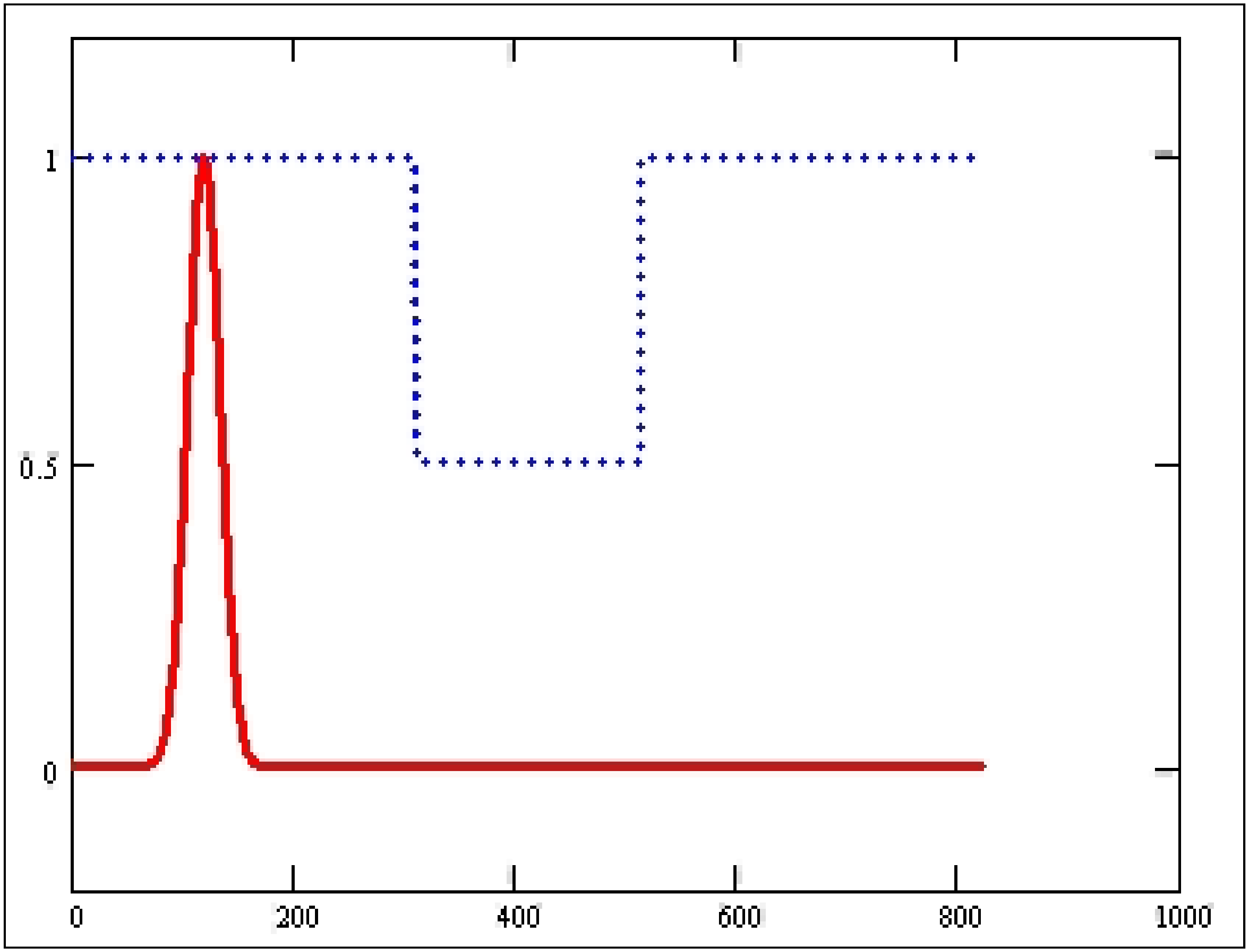
Assume an input pulse with a Gaussian temporal profile.

Study three cases:

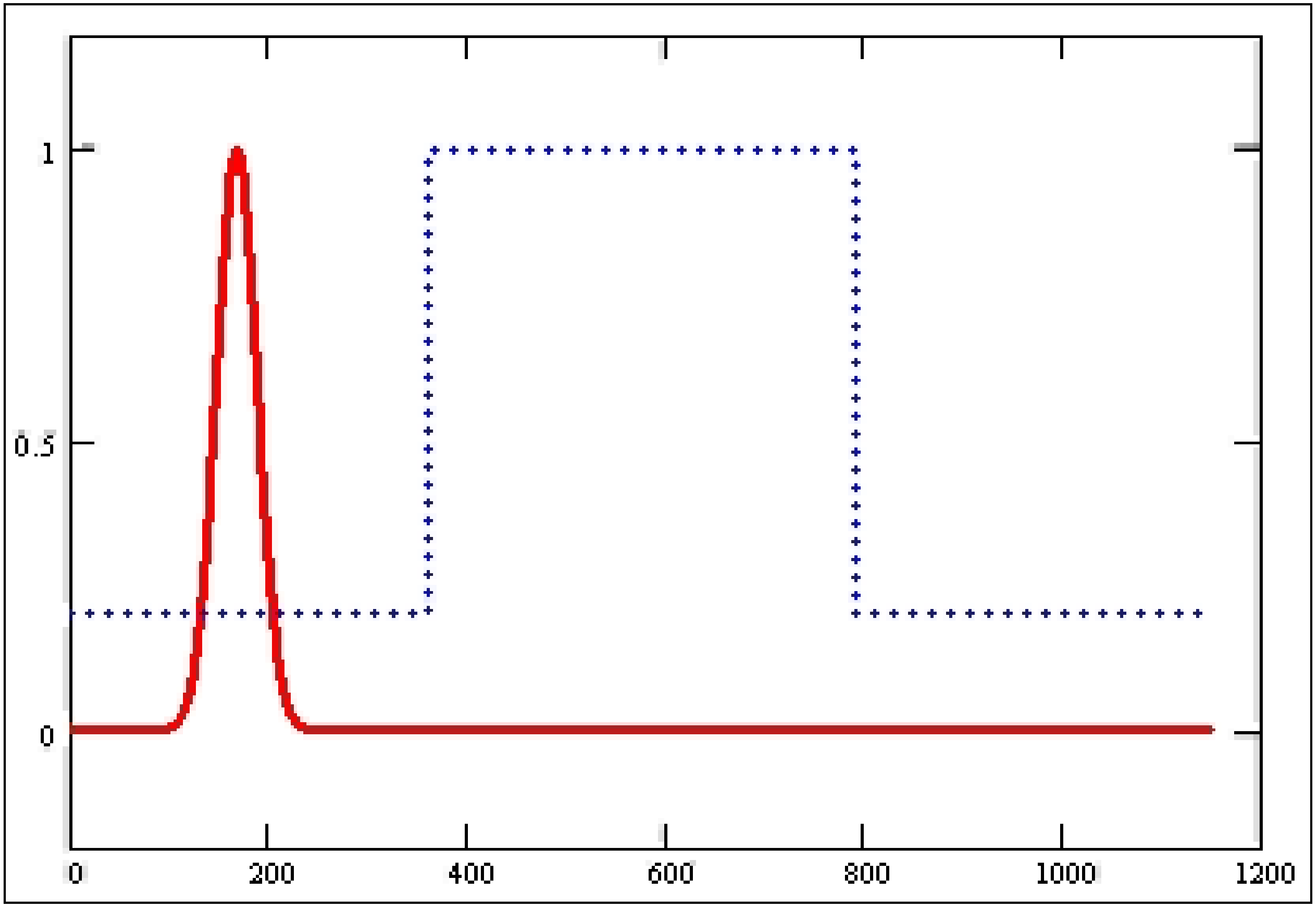
Slow light $v_g = 0.5$ c

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

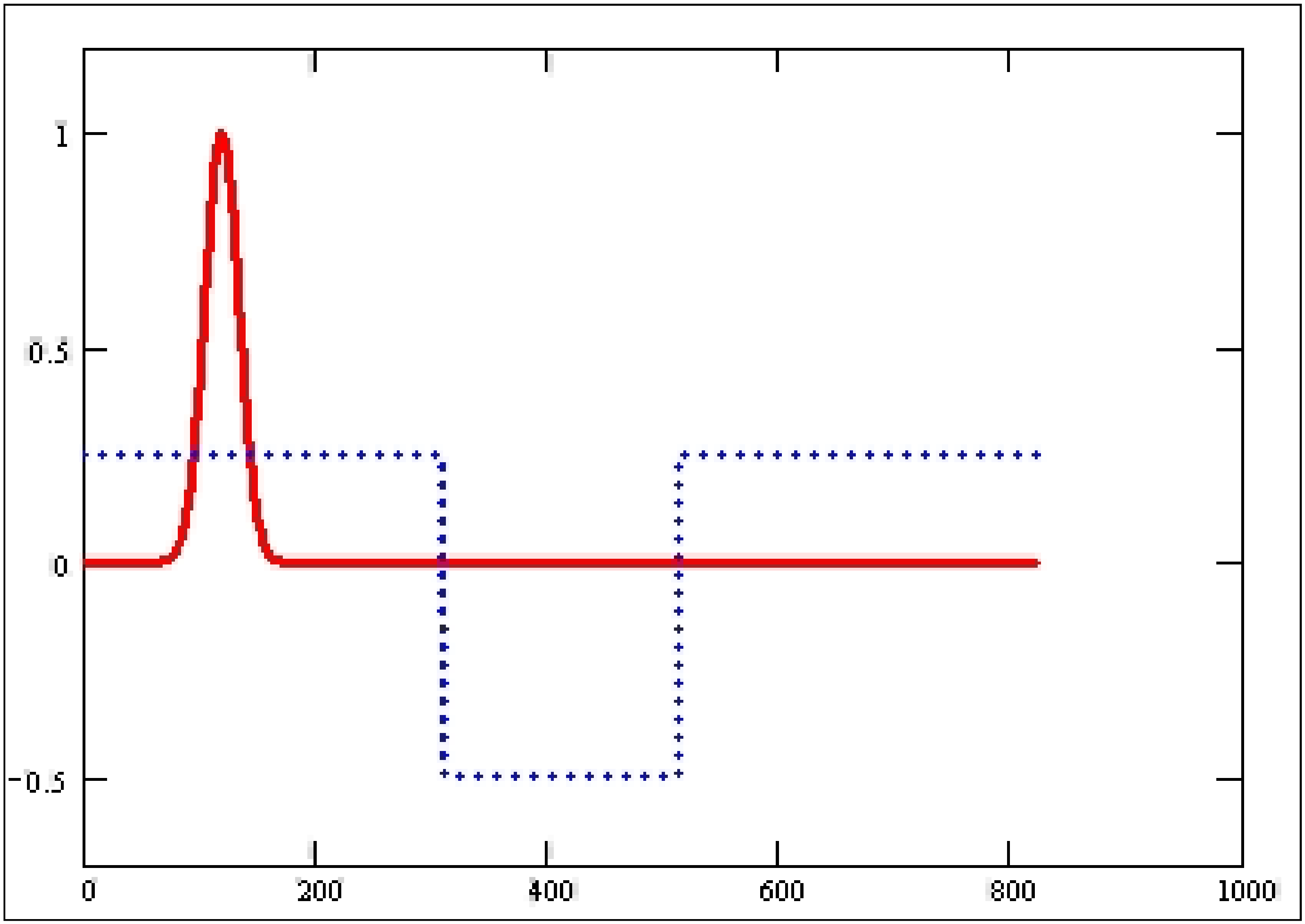
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5\ c$)



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

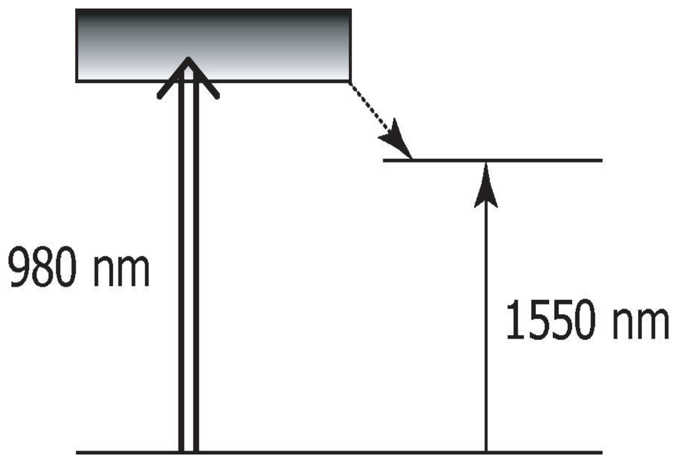


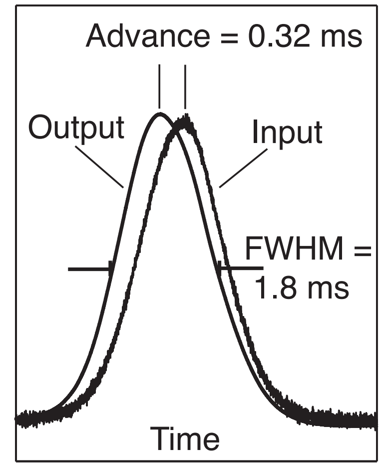
Pulse Propagation through a Fast-Light Medium (n_g = -.5, v_g = -2 c)

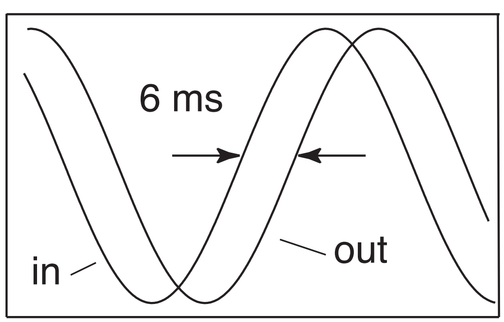


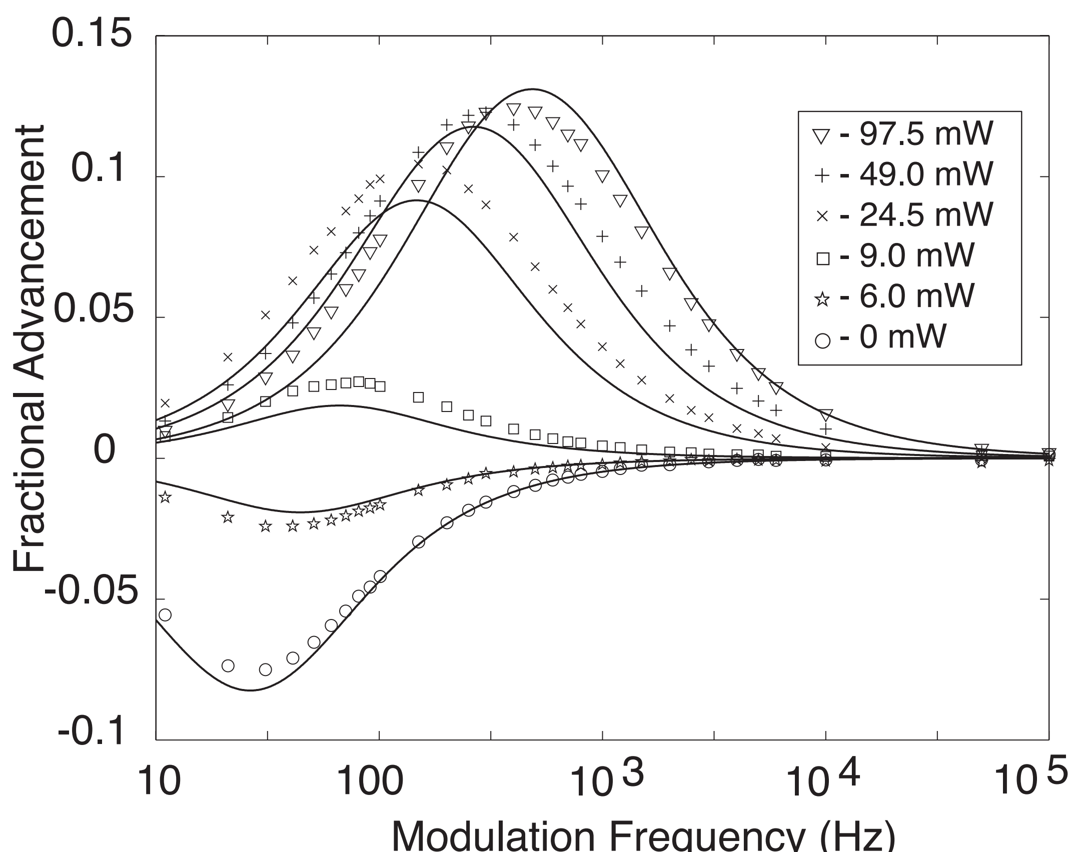
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



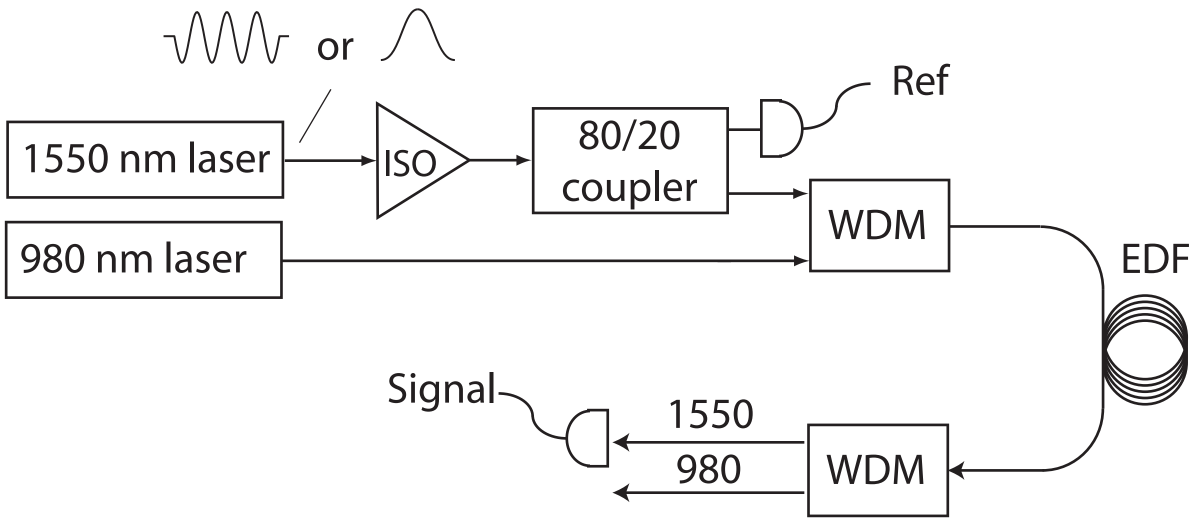






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

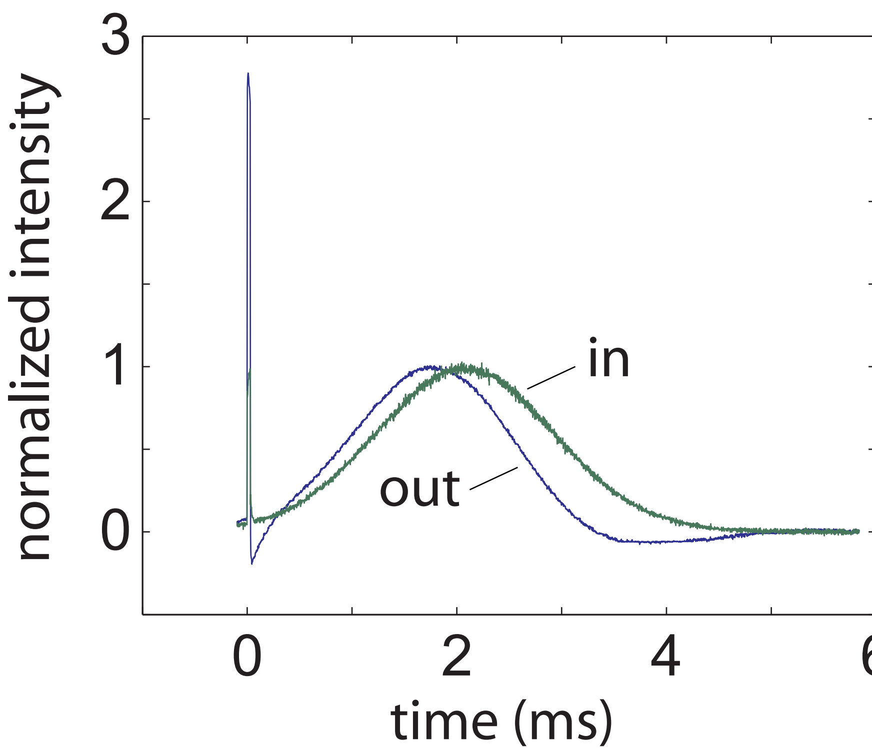
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



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

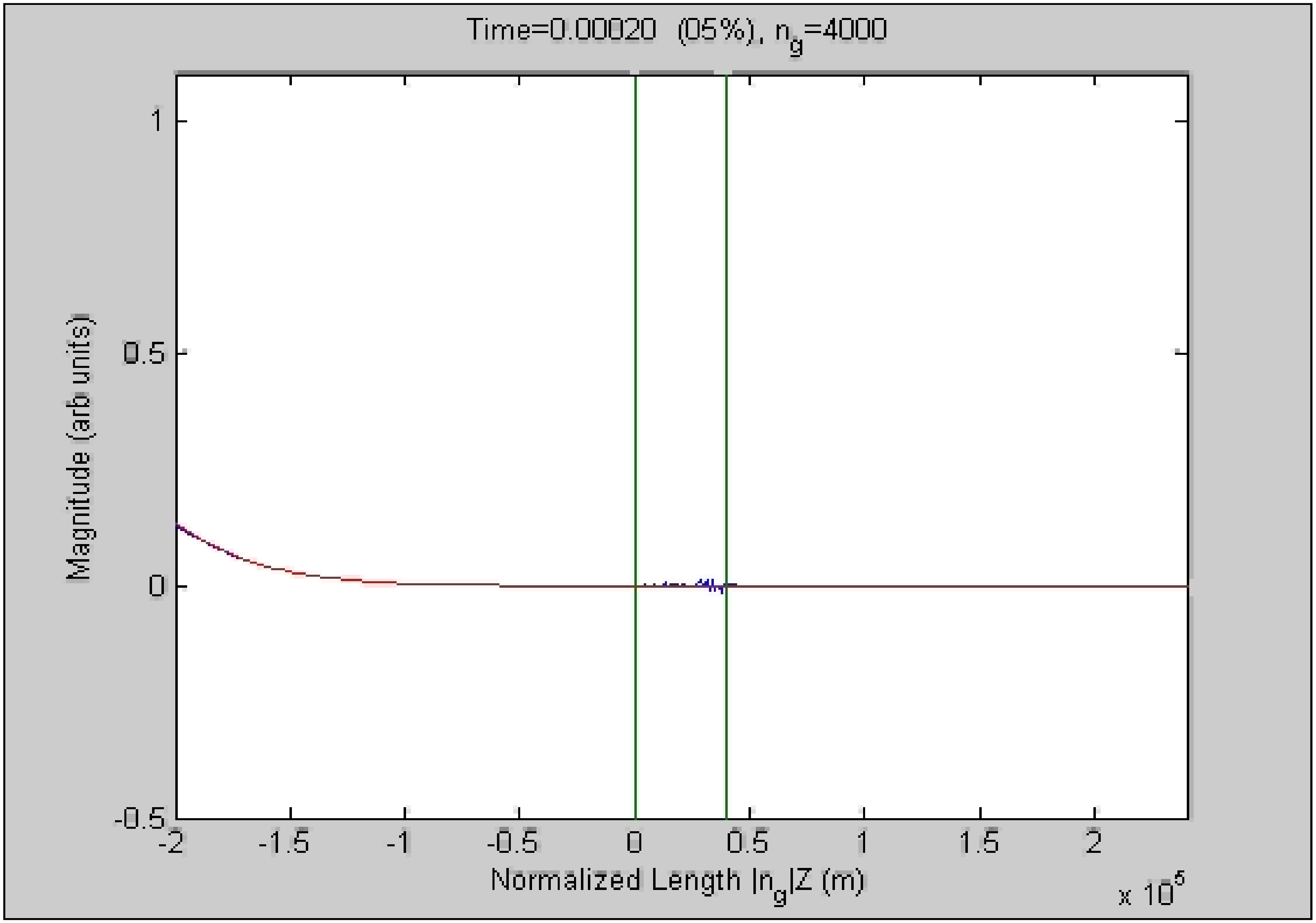
Procedure

- cutback method
- couplers embedded in fiber



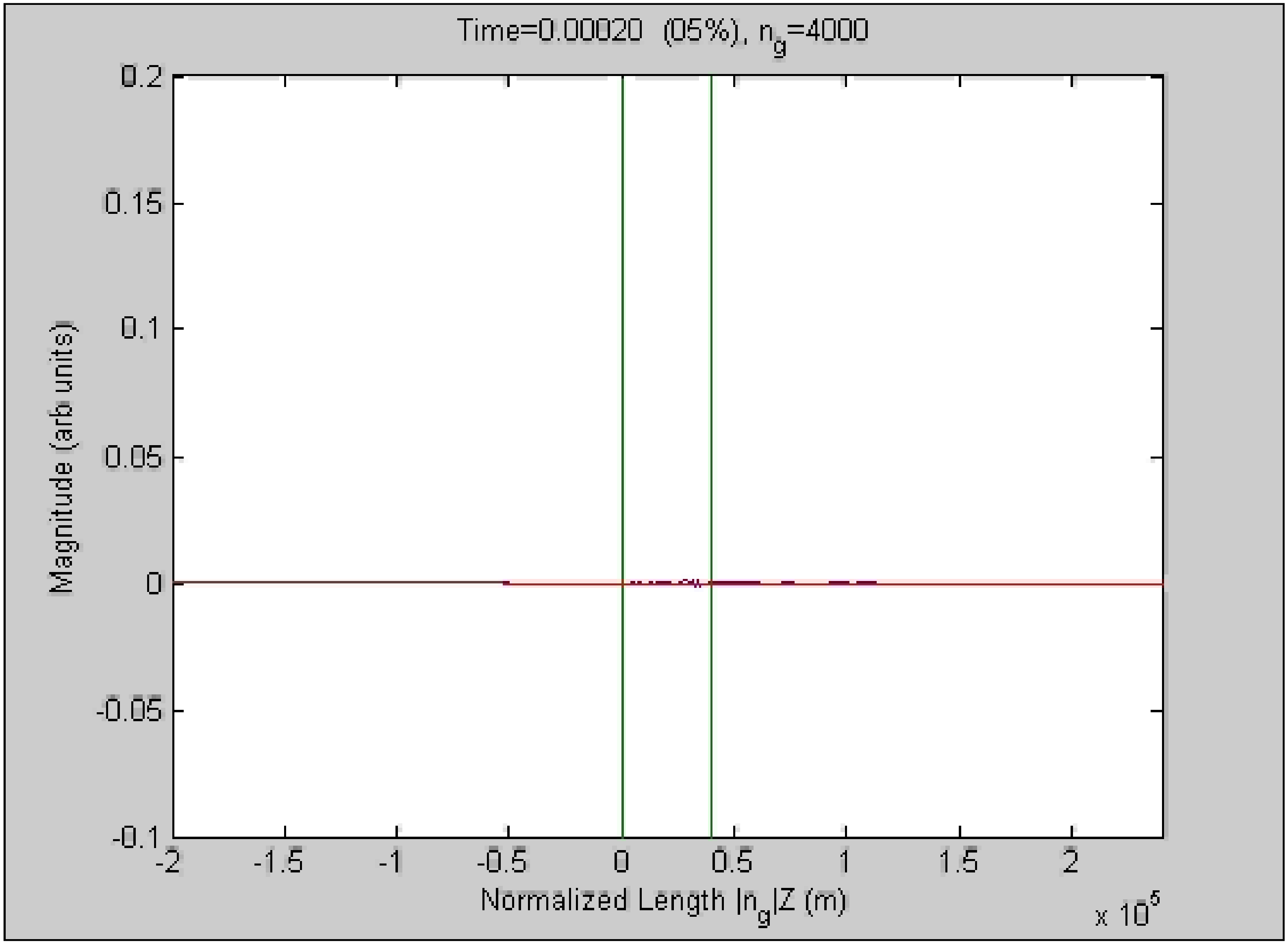
Experimental Results: Backward Propagation in Erbium-Doped Fiber

Normalized: (Amplification removed numerically)

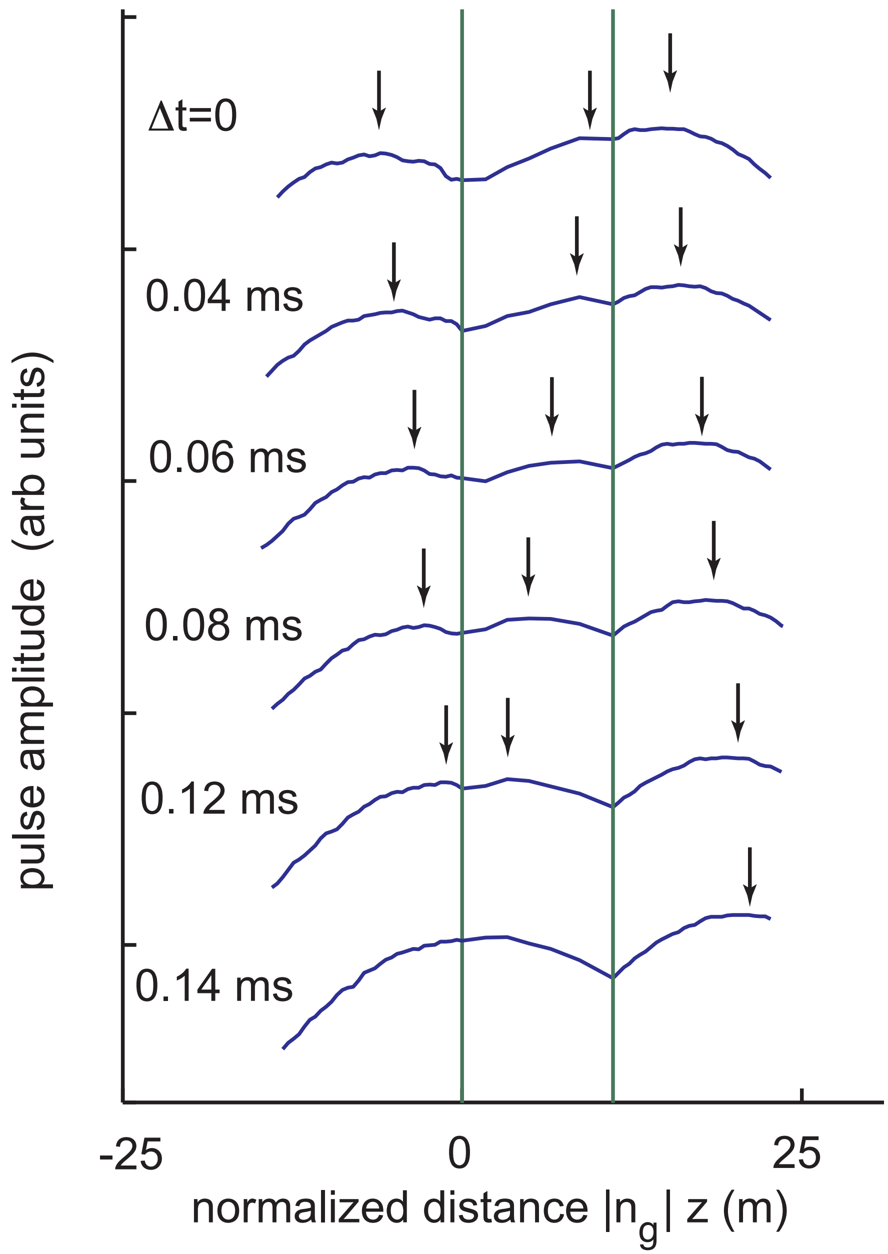


Experimental Results: Backward Propagation in Erbium-Doped Fiber

Un-Normalized



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



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

Summary:

"Backwards" propagation is a realizable physical effect.

Causality and Superluminality

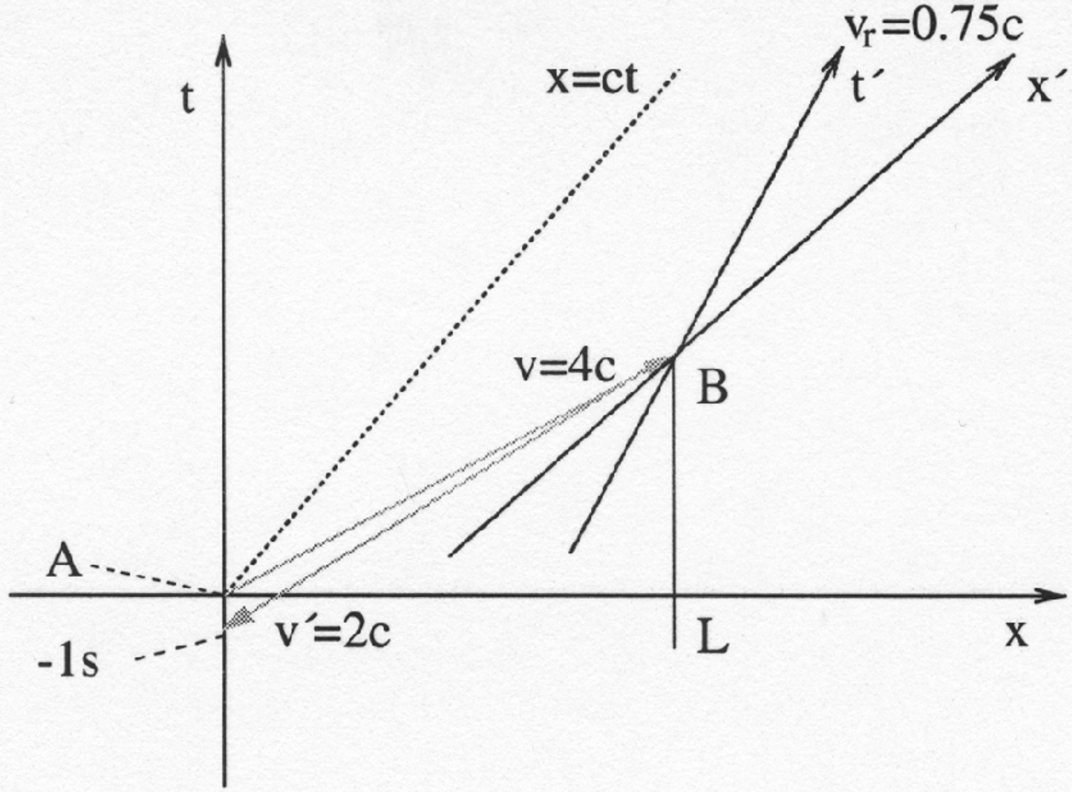
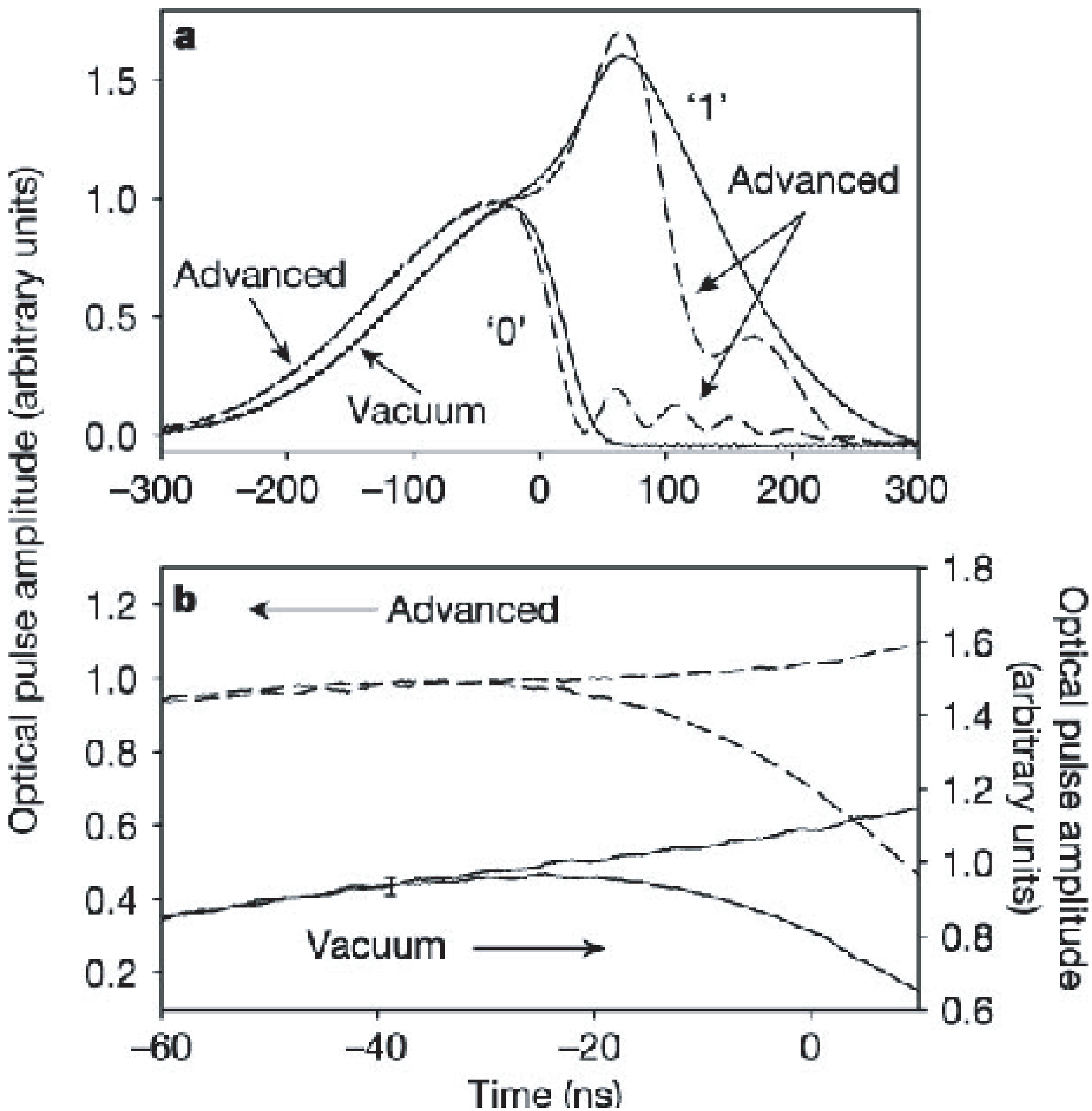


Fig. 6 Coordinates of two inertial observers **A** (0,0) and **B** with $O(x,t)$ and $O'(x',t')$ moving with a relative velocity of $0.75c$. The distance L between **A** and **B** is 2 000 000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v_s' = 2c$. The numbers in the example are chosen arbitrarily. The signal returns −1 s in the past in **A**.

Ann. Phys. (Leipzig) 11, 2002.

Information Velocity in a Fast Light Medium

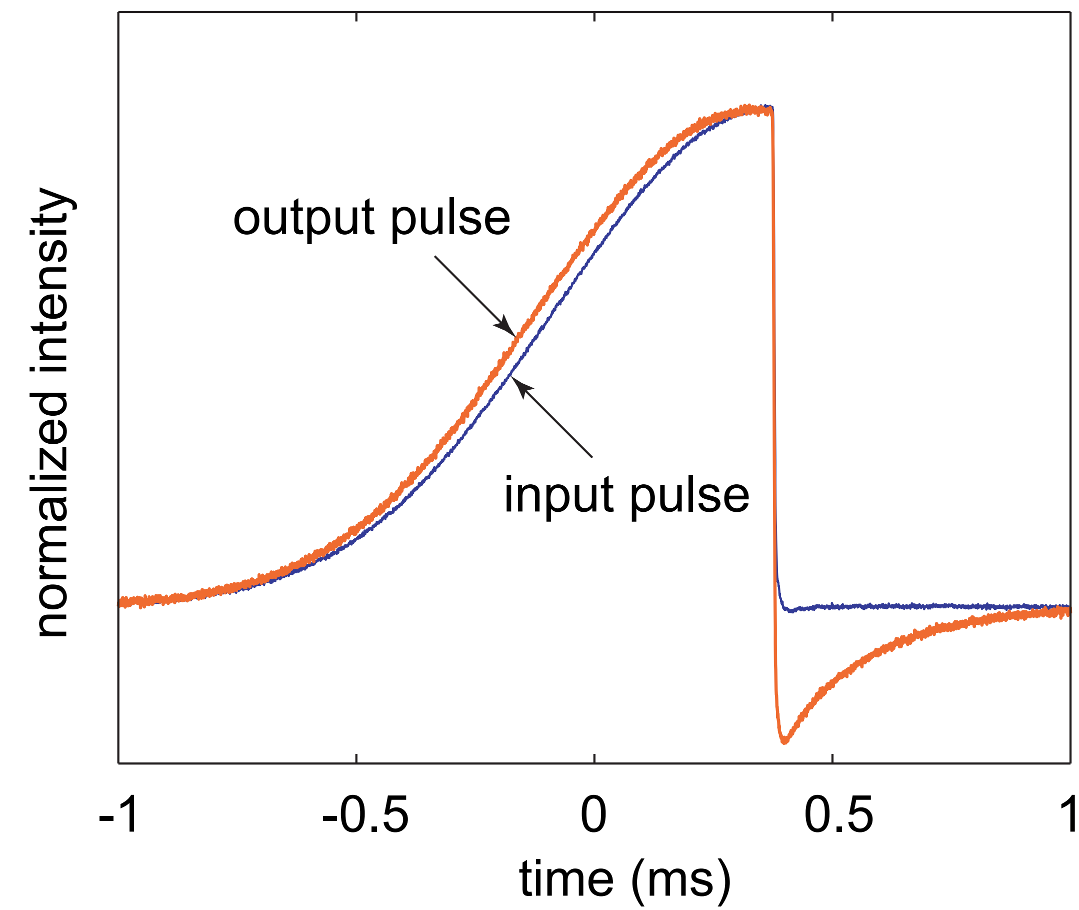


M.D. Stenner, D.J. Gauthier, and M.I. Neifeld, Nature,425 695 (2003).

Pulses are not distinguishable "early."

$v_i \leq c$

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?)

Bigelow, Lepeshkin, Shin, and Boyd, J. Physics: Condensed Matter 18, 3117 (2006).

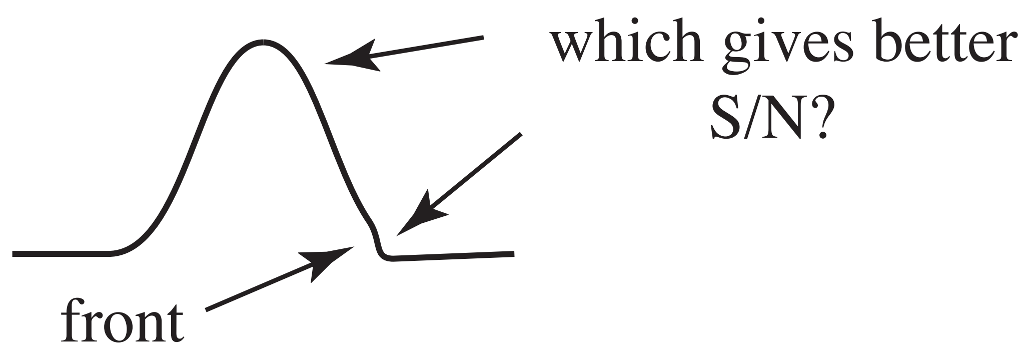
Information Velocity – Tentative Conclusions

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.



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**

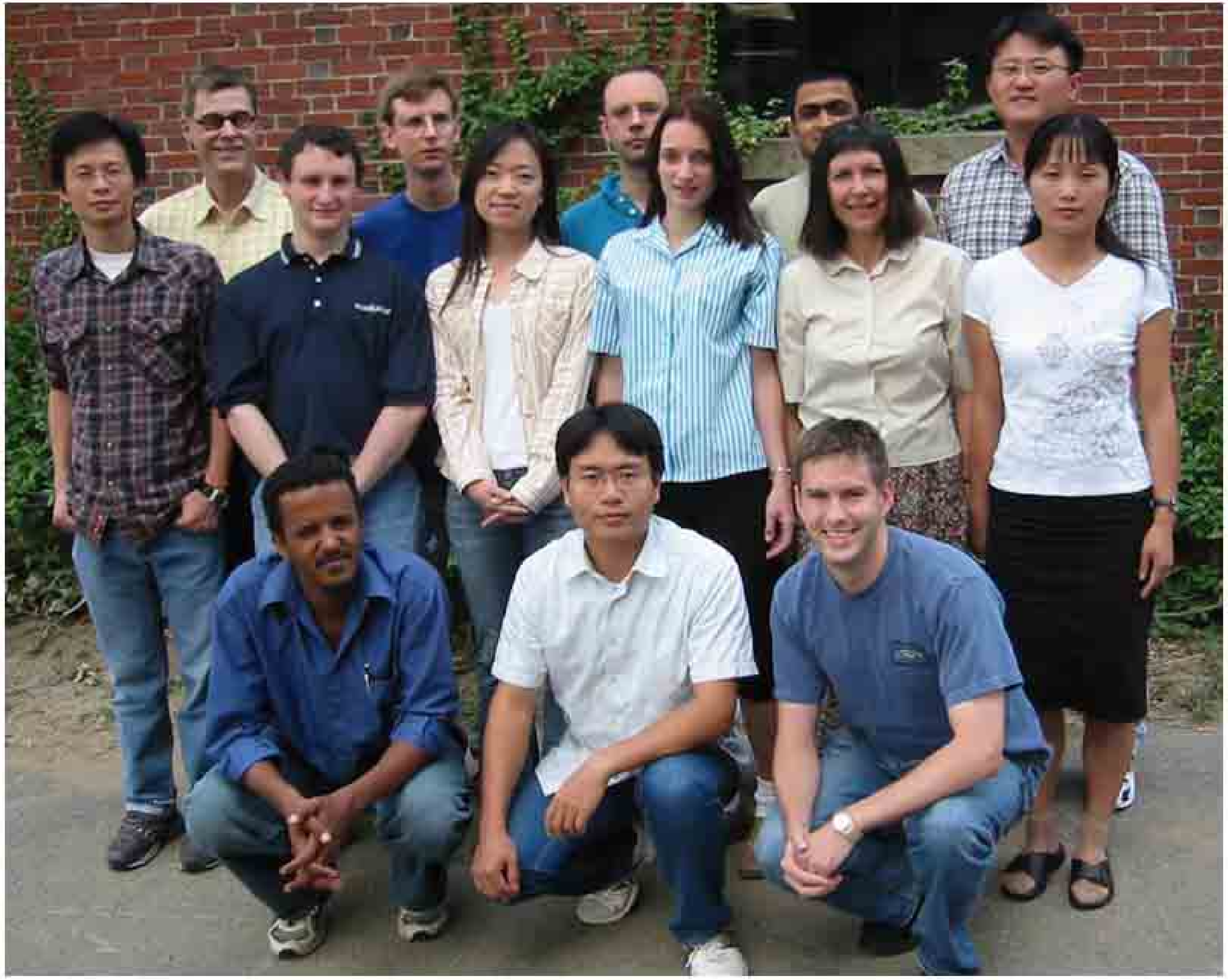
Summary

Slow-light techniques hold great promise for applications in telecom and quantum information processing

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

Different methods under development possess complementary regimes of usefullness

Special Thanks to My Students and Research Associates



Thank you for your attention.

And thanks to NSF and DARPA for financial support!

Thank you for your attention!