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

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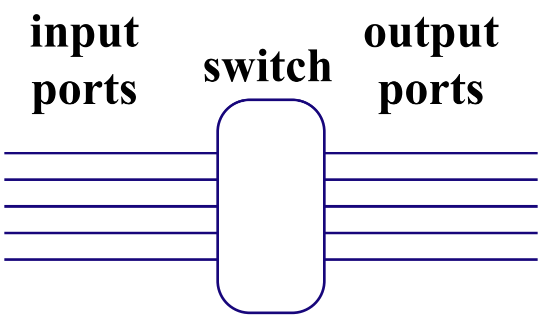
with George Gehring, Giovanni Piredda, Paul Narum,
Aaron Schweinsberg, Zhimin Shi, Heedeuk Shin,
Joseph Vornehm, Petros Zerom, and many others

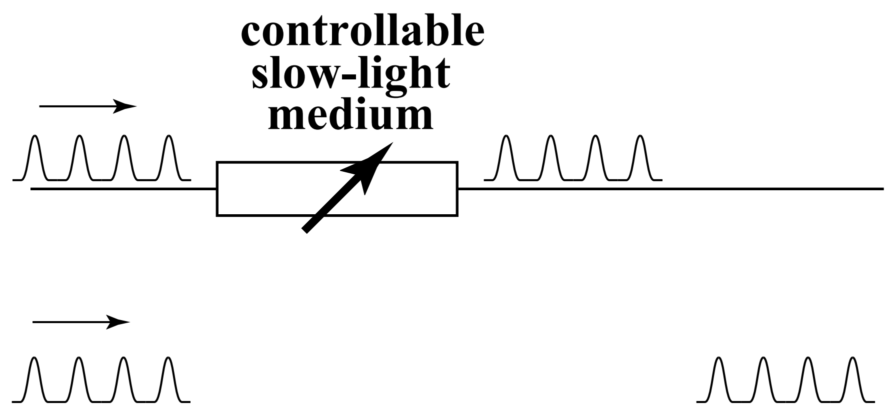
Presented at the OSA Topical Meeting on Slow Light, July 9-11, 2007

Slow Light and Optical Buffers

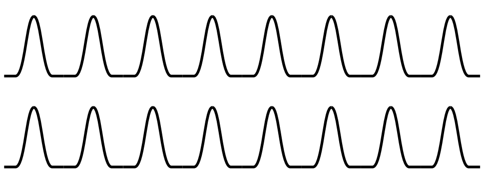
All-Optical Switch



Use Optical Buffering to Resolve Data-Packet Contention



But what happens if two data packets arrive simultaneously?

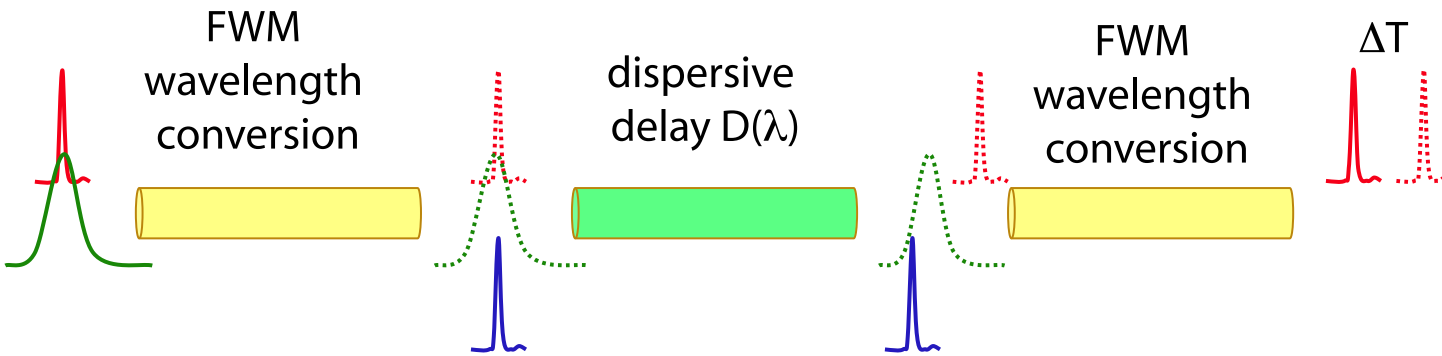


Controllable slow light for optical buffering can dramatically increase system performance.

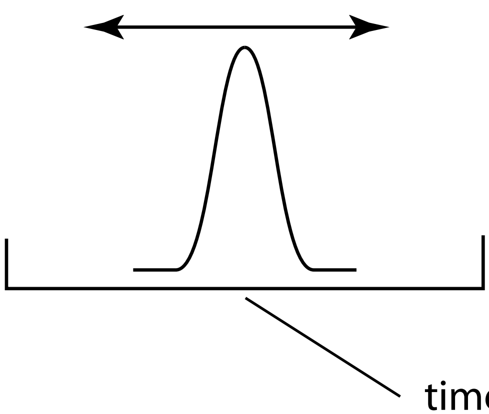
Daniel Blumenthal, UC Santa Barbara; Alexander Gaeta, Cornell University; Daniel Gauthier, Duke University; Alan Willner, University of Southern California; Robert Boyd, John Howell, University of Rochester

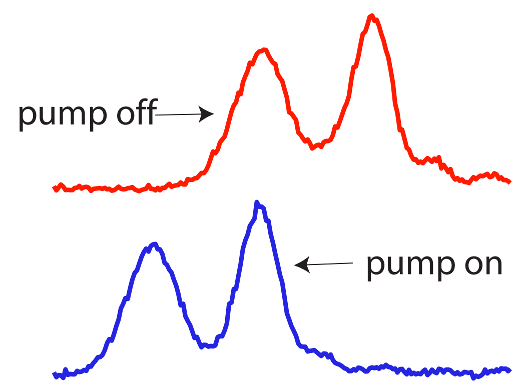
Slow-Light Telecom Buffer / Regeneration System

- Optical Buffering – Need many pulse-widths of delay
  Use the conversion / dispersion method of Gaeta and others



- Regeneration of Pulse Timing –
  Single pulse-width of delay adequate, but need precise control
  Use “true” slow light (SBS?)





Slow and Fast Light and Optical Resonances

Pulses propagate at the group velocity given by

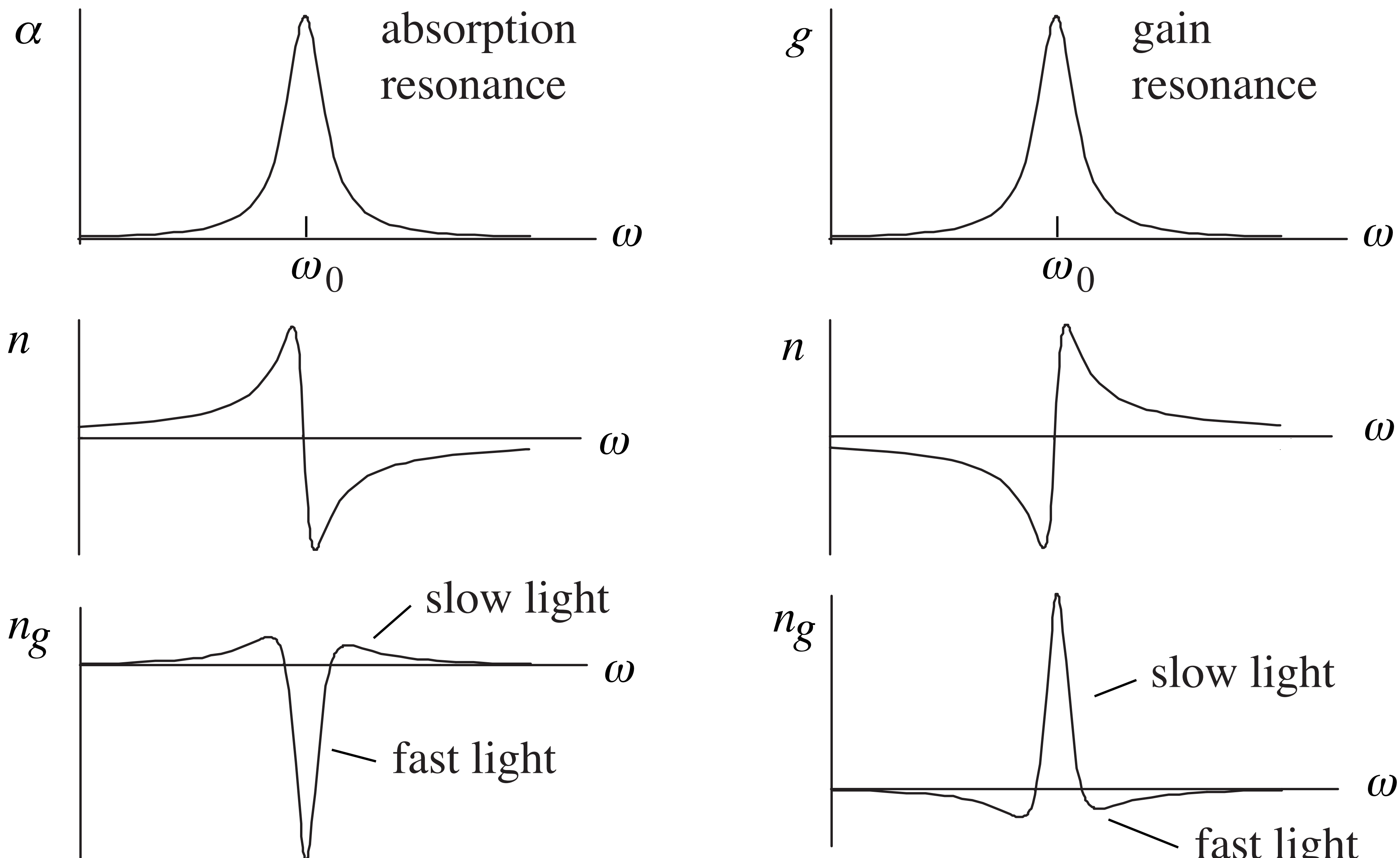
$$v_g = \frac{c}{n_g} \qquad n_g = n + \omega \frac{dn}{d\omega}$$

Want large dispersion to obtain extreme group velocities

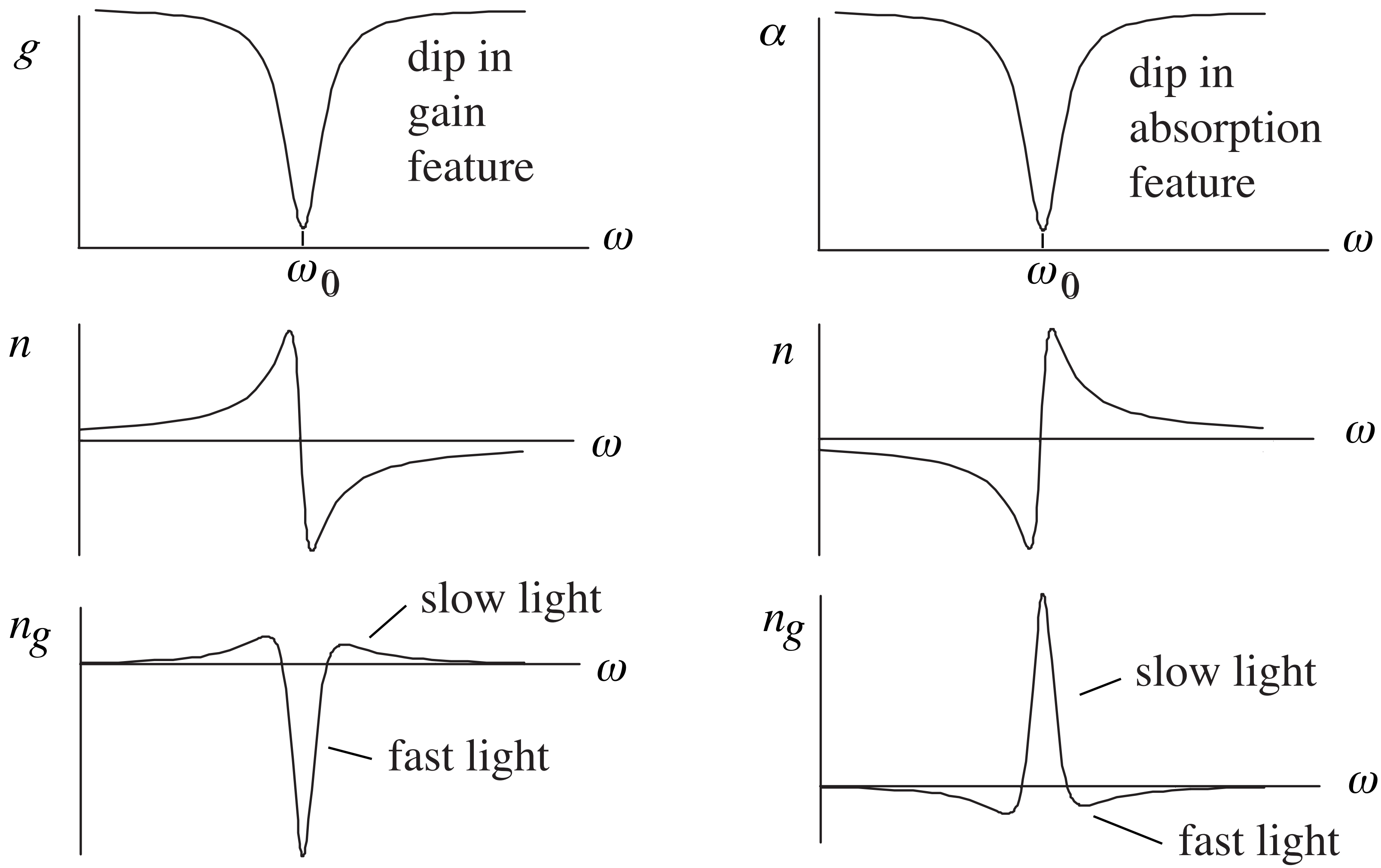
Sharp spectral features produce large dispersion.

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.

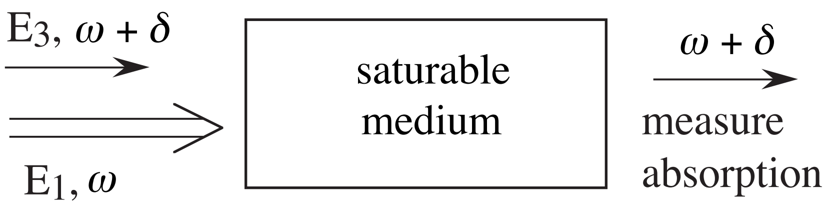
Challenge / Goal (2003)

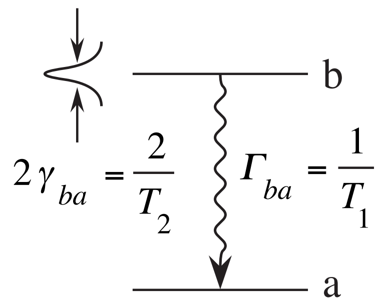
Slow light in a room-temperature, solid-state material.

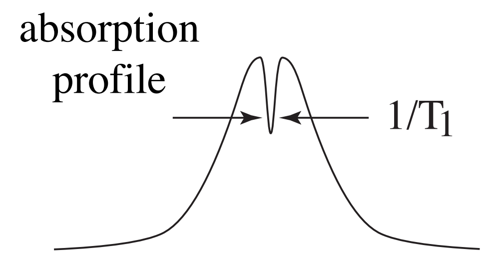
Our solution:

Slow light *via* coherent population oscillations (CPO),
a quantum coherence effect related to EIT but which is less
sensitive to dephasing processes.

Slow Light 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)

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

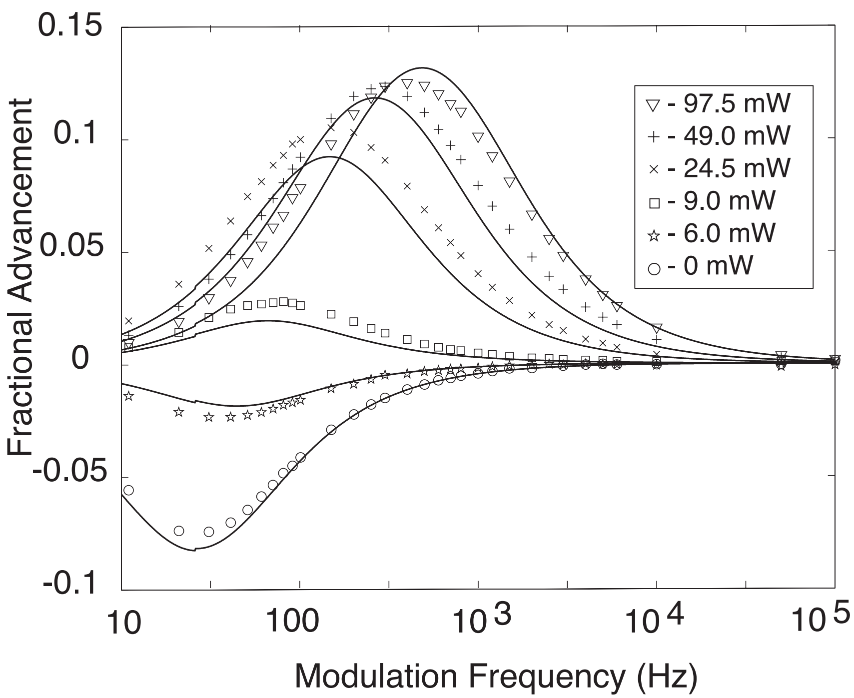
Works with single beam (self-delayed)

Delay can be controlled through input intensity

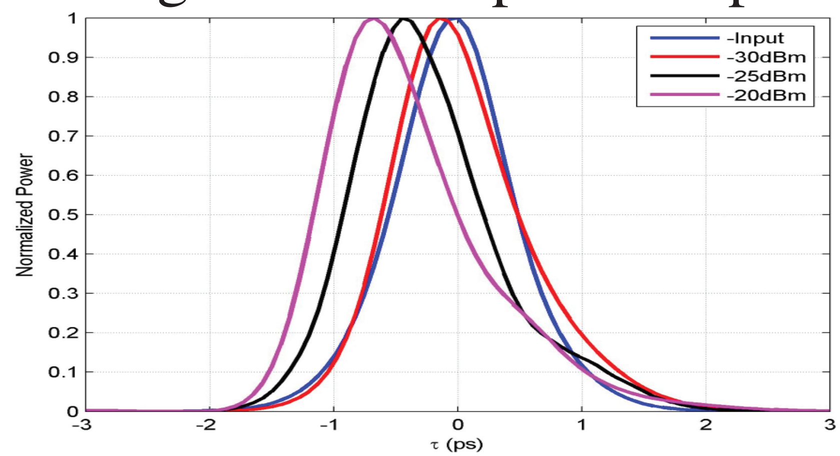
Slow Light via Coherent Population Oscillations

- 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.

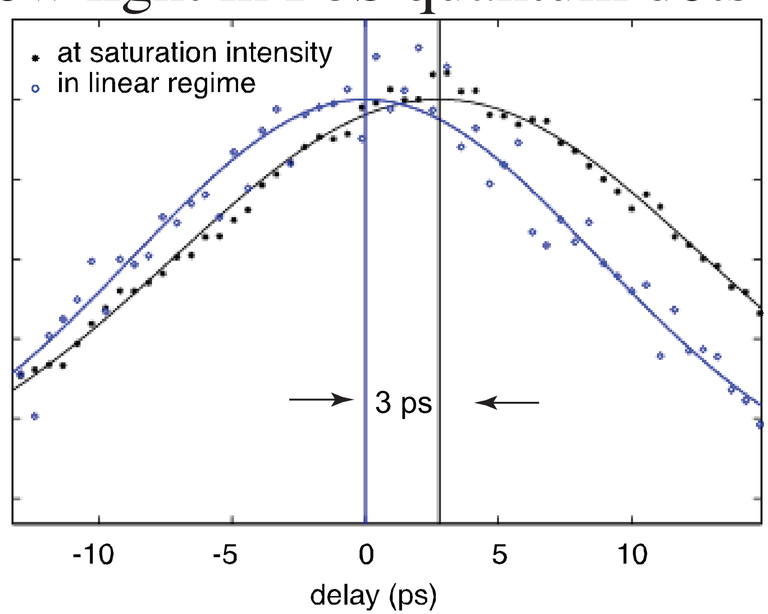
- Slow and fast light in an EDFA



- Slow light in a SC optical amplifier



- Slow light in PbS quantum dots



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.

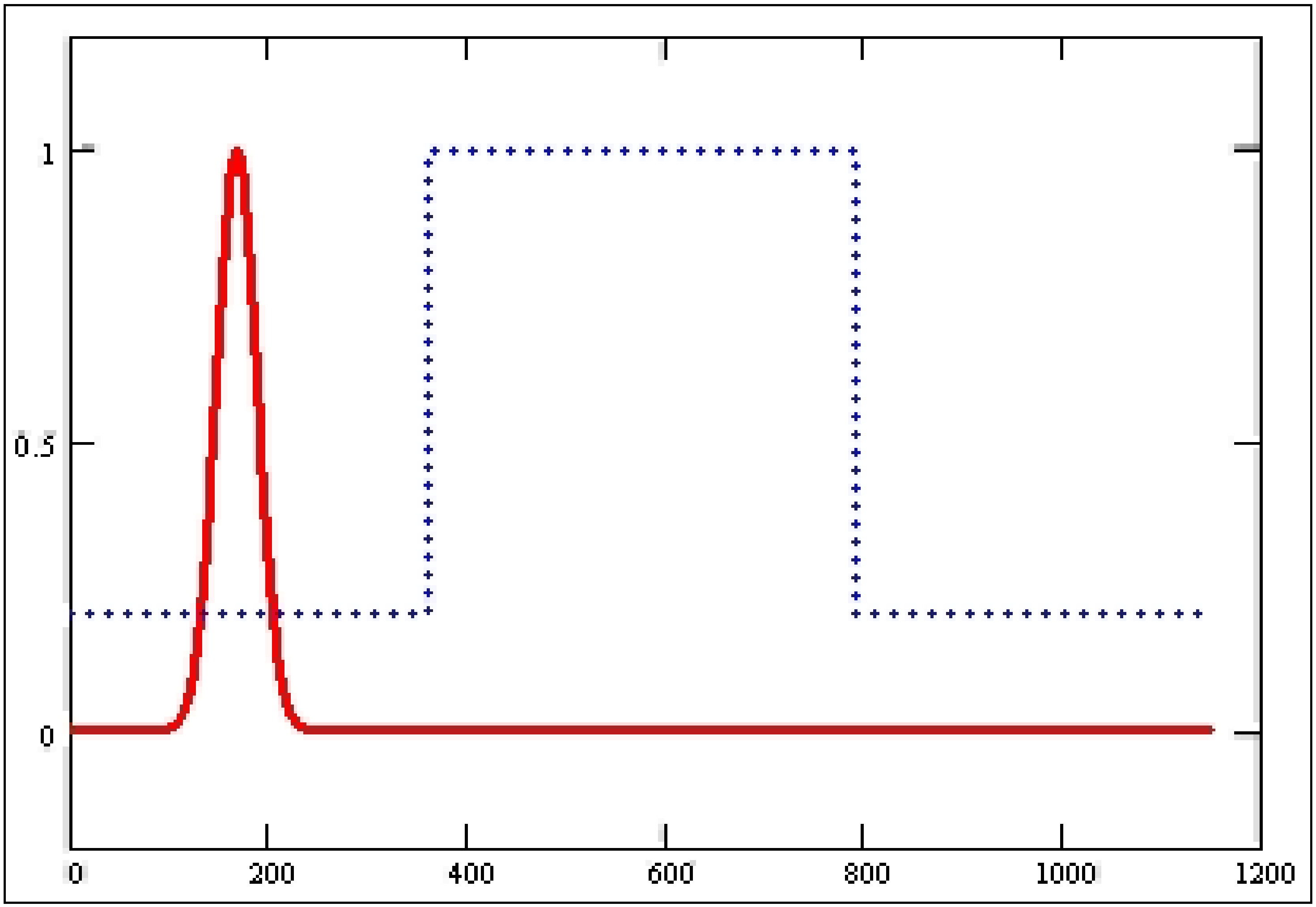
Study three cases:

Slow light $v_g = 0.5\ c$

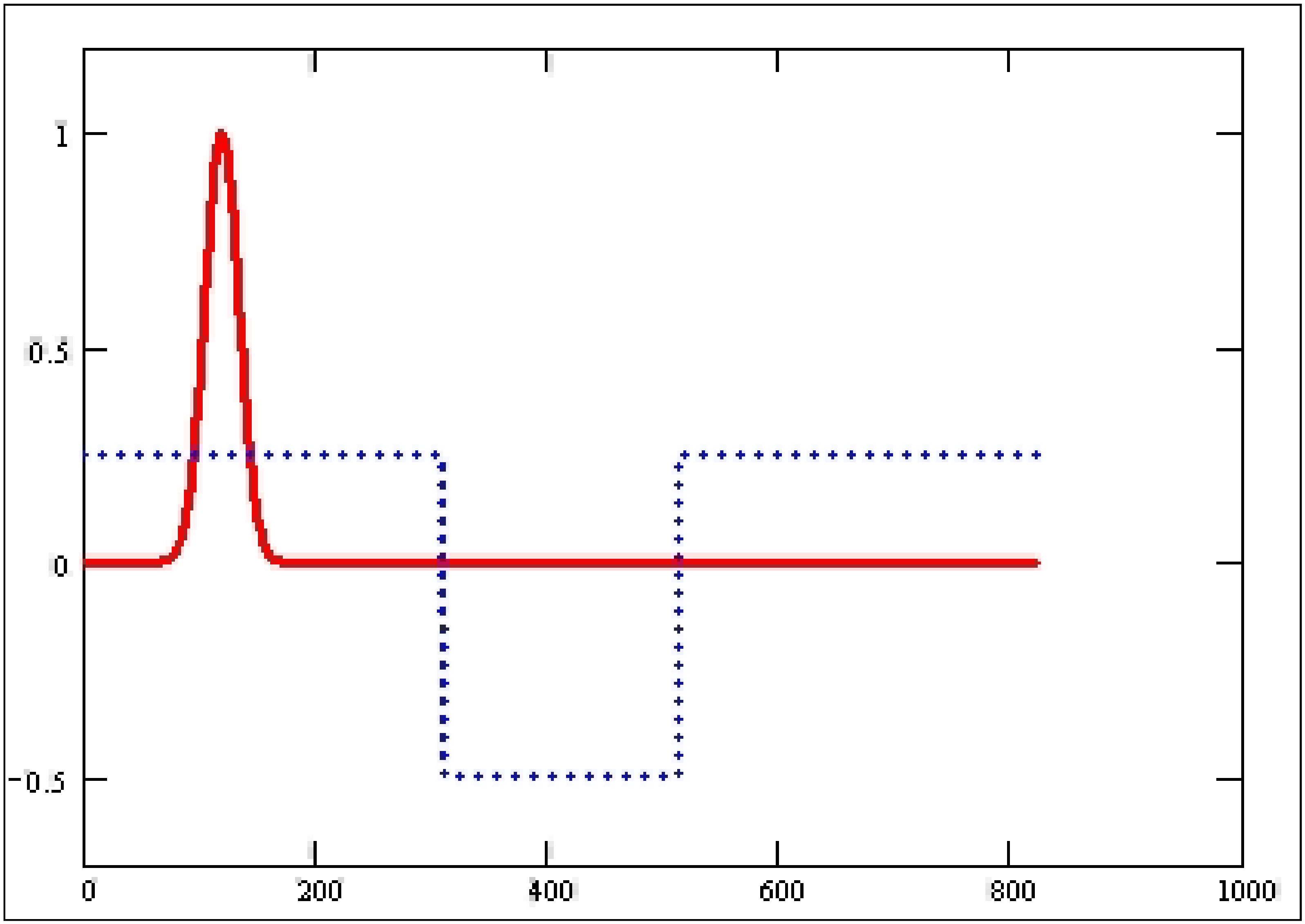
Fast light $v_g = 5\ c$ and $v_g = -2\ c$

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

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

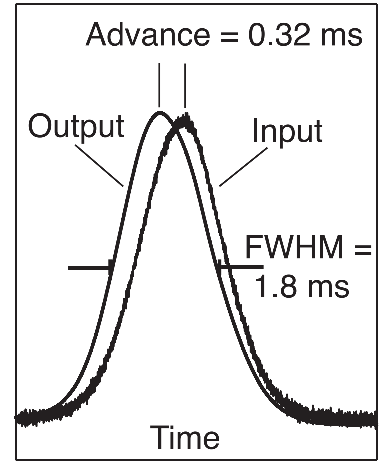


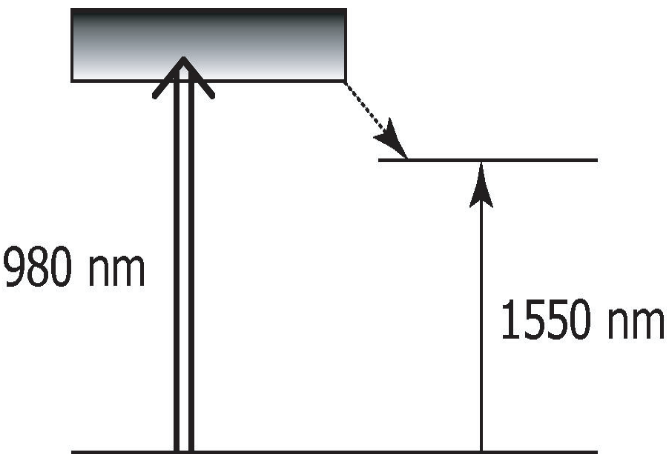
Pulse Propagation through a Backwards-Light Medium (n_g = -.5, v_g = -2 c)

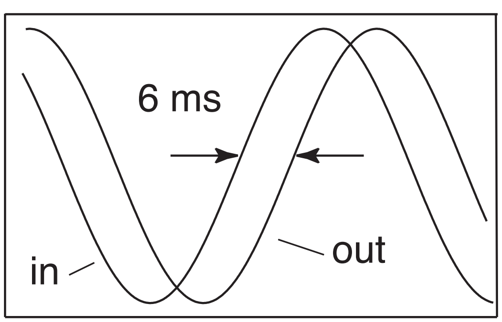


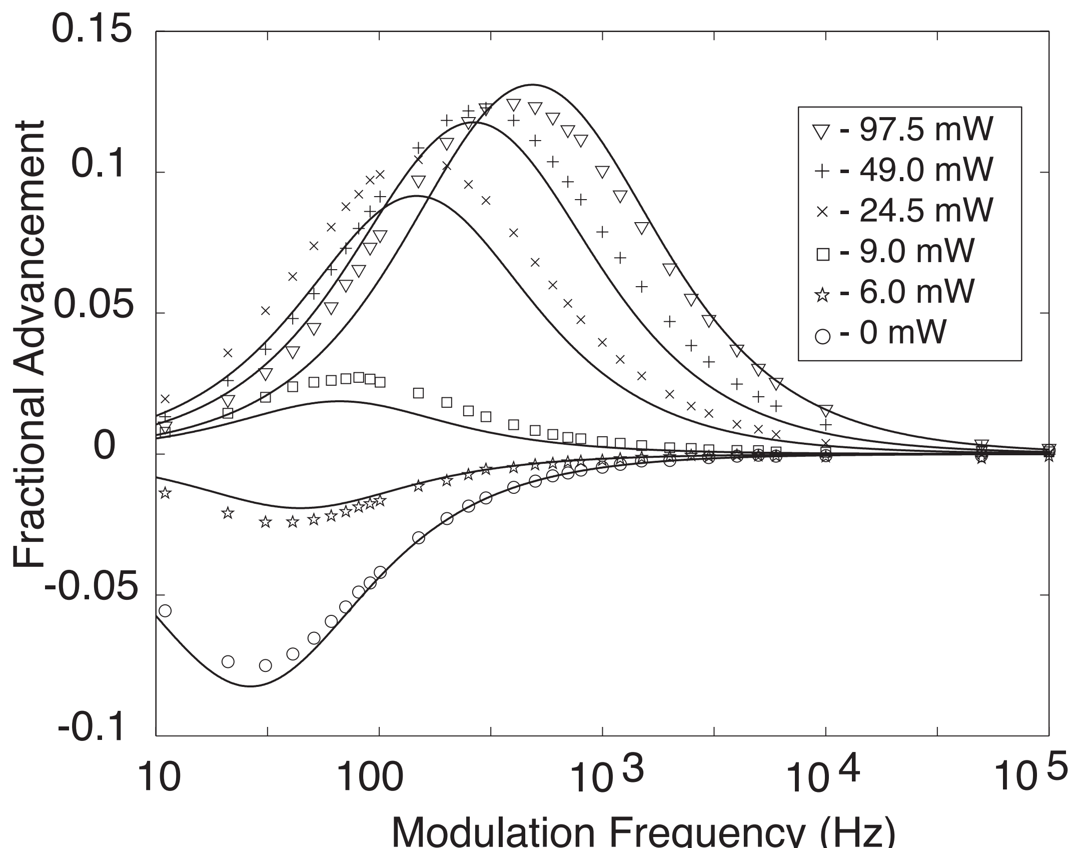
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



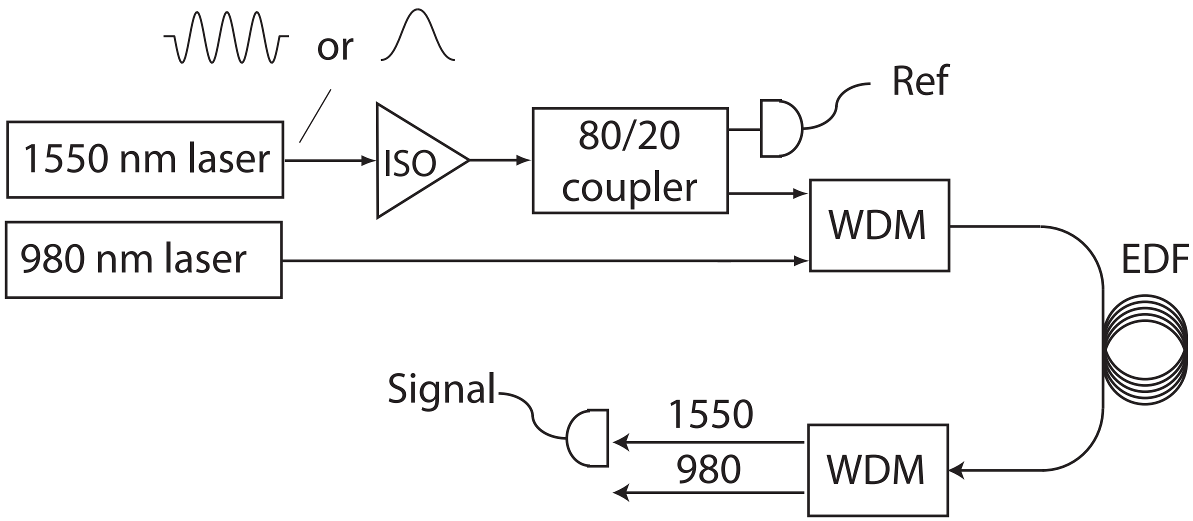






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

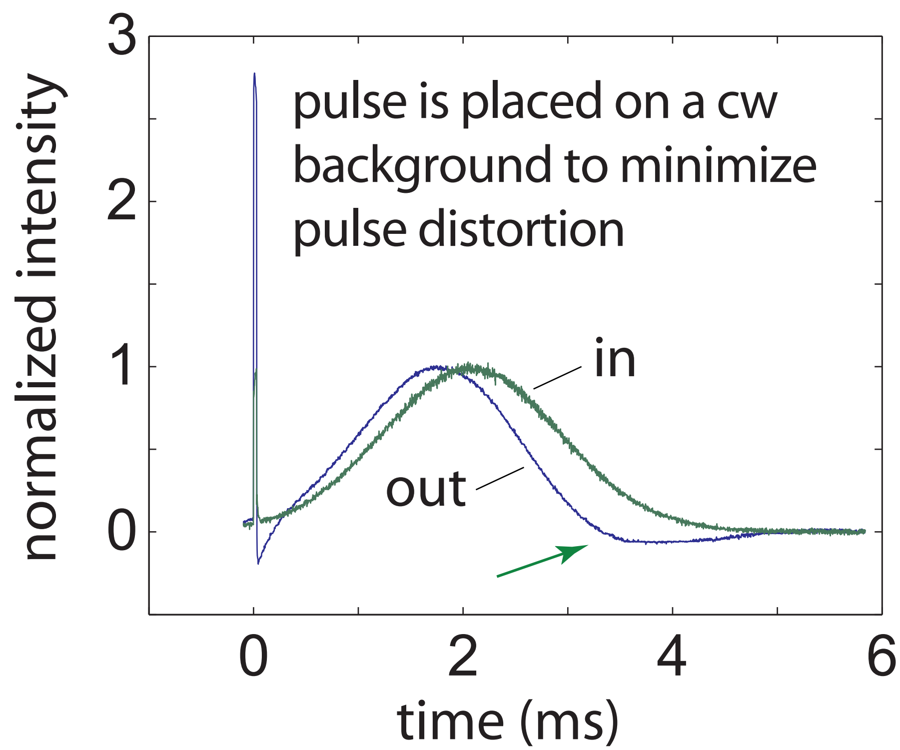
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



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

Procedure

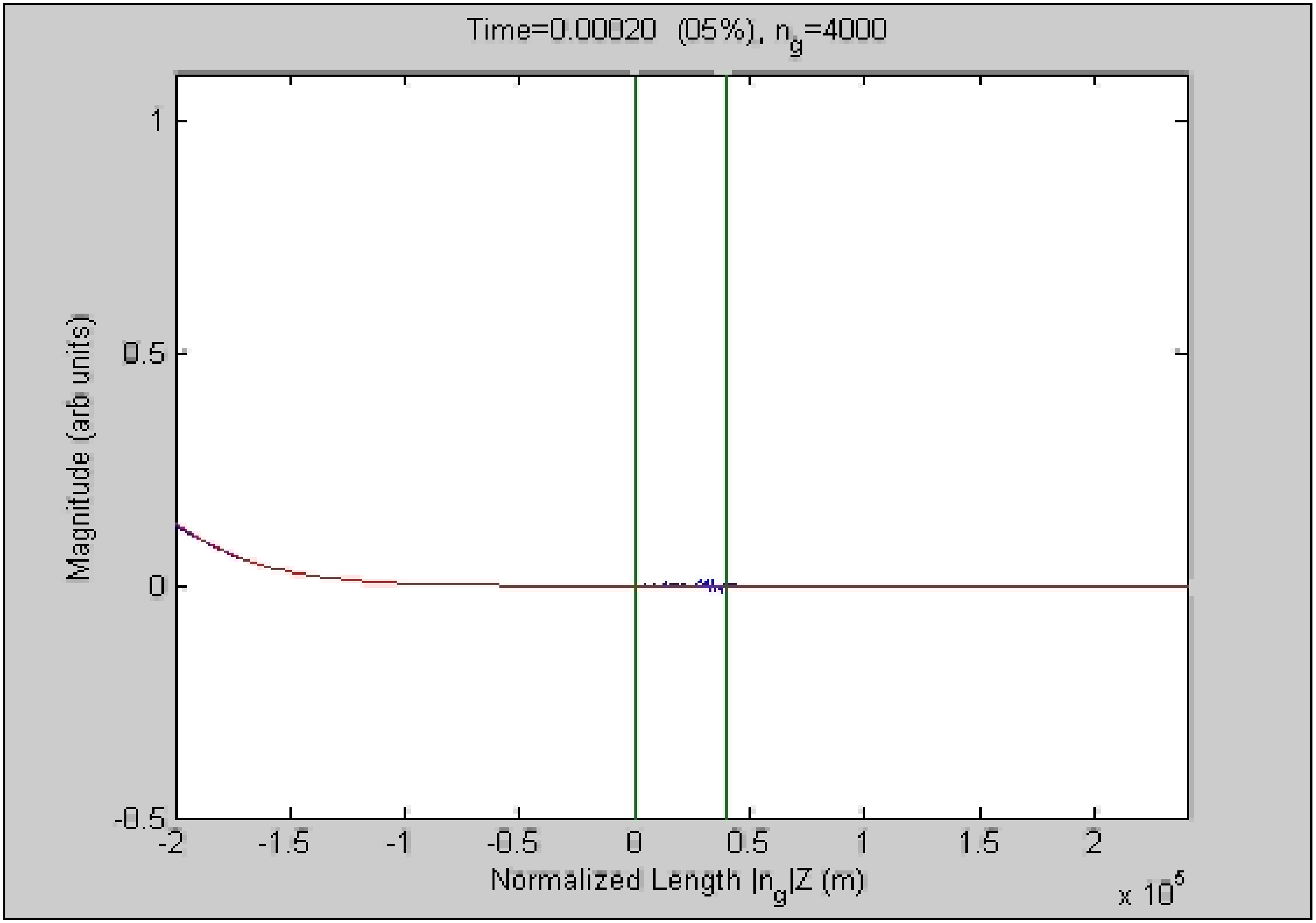
- cutback method
- couplers embedded in fiber



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)



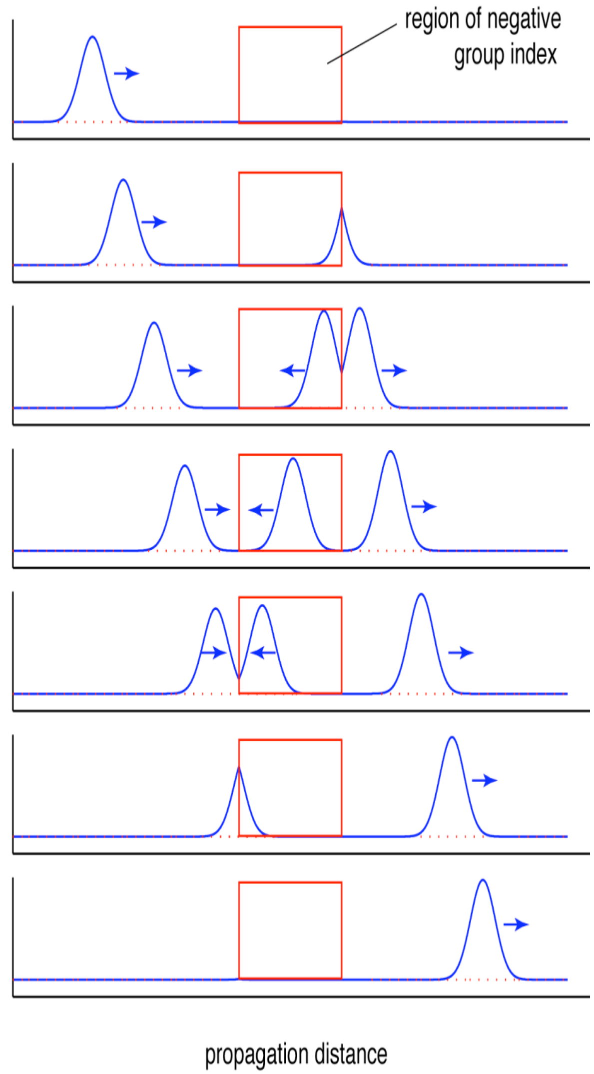
Observation of "Backwards" Pulse Propagation

- A strongly counterintuitive phenomenon

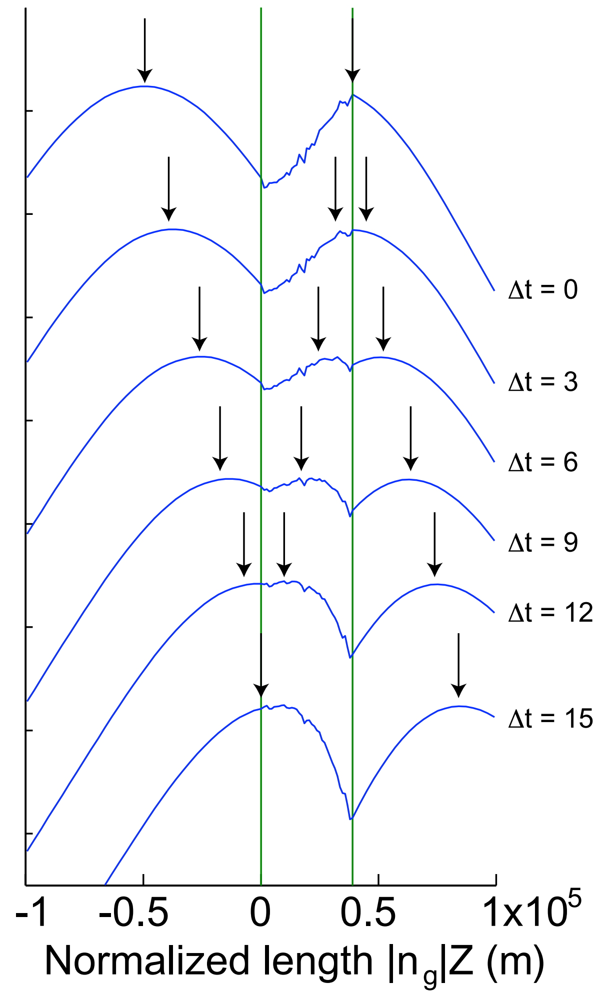
- But entirely consistent with established physics

- 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

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

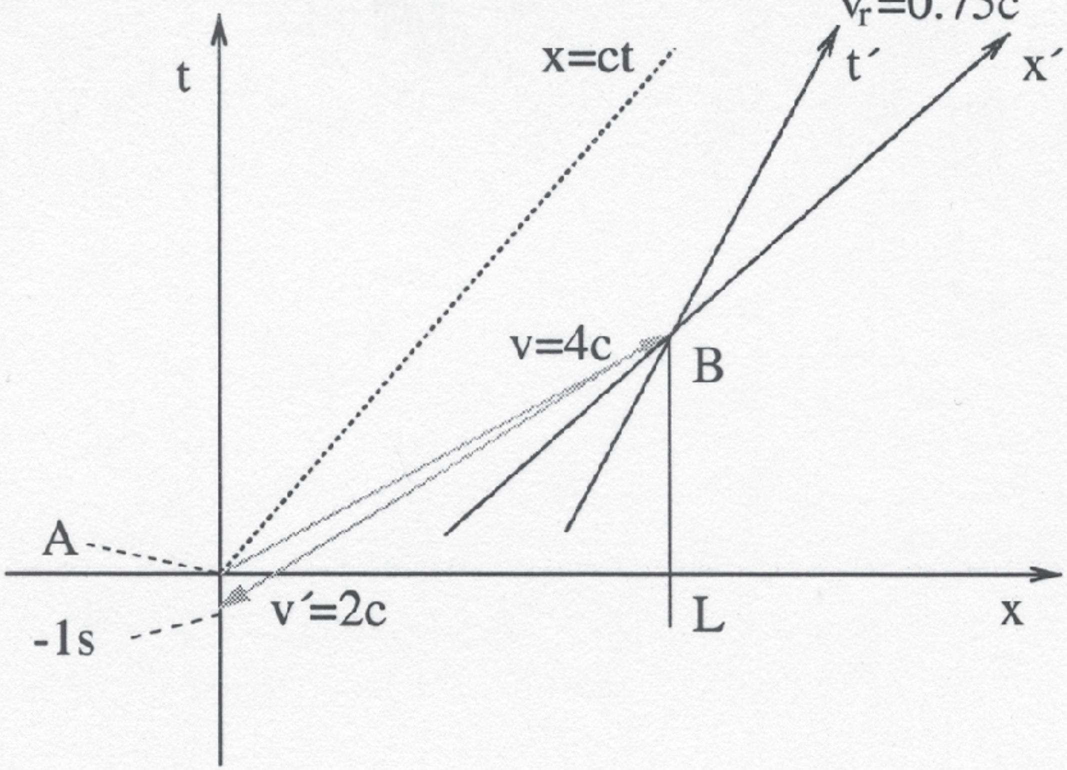
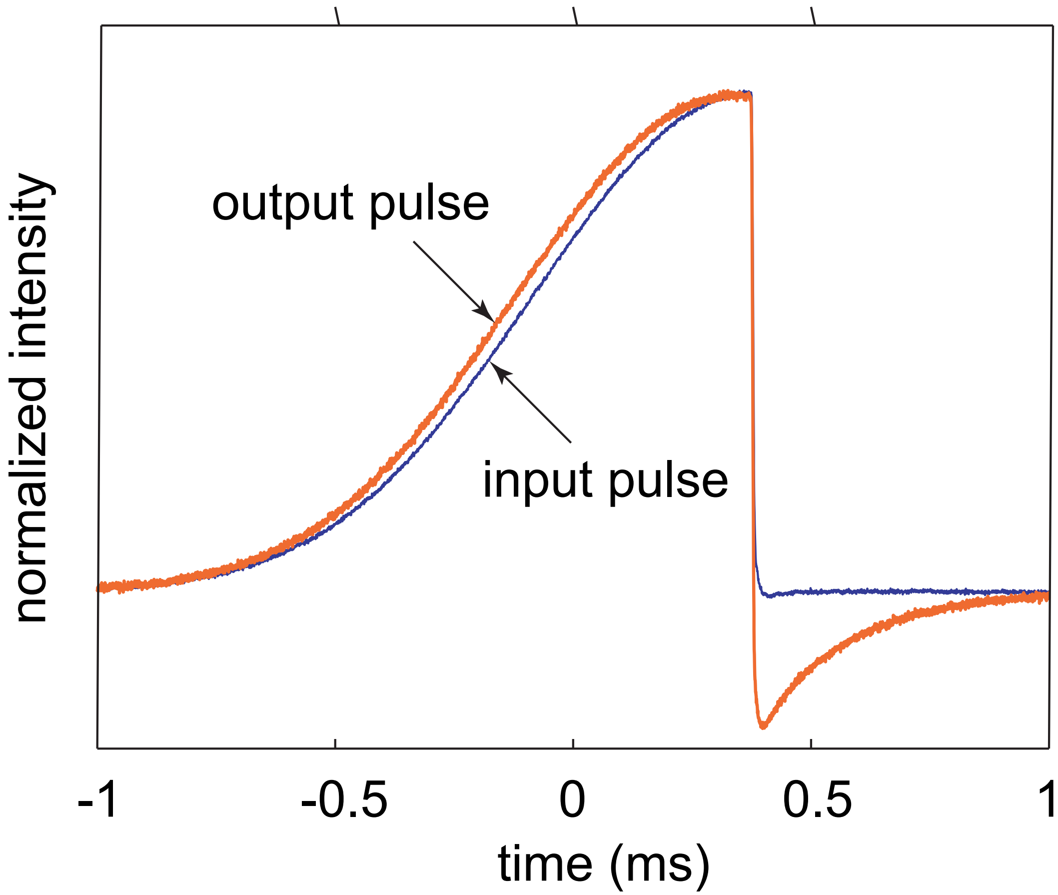


Fig. 6 Coordinates of two inertial observers **A** (0,0) and **B** with $O(x,t)$ and $O'(x',t')$ moving with a relative velocity of 0.75c. The distance L between **A** and **B** is 2000000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v_s' = 2c$. The numbers in the example are chosen arbitrarily. The signal returns −1 s in the past in **A**.

Ann. Phys. (Leipzig) 11, 2002.

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



Smooth part of pulse propagates at group velocity

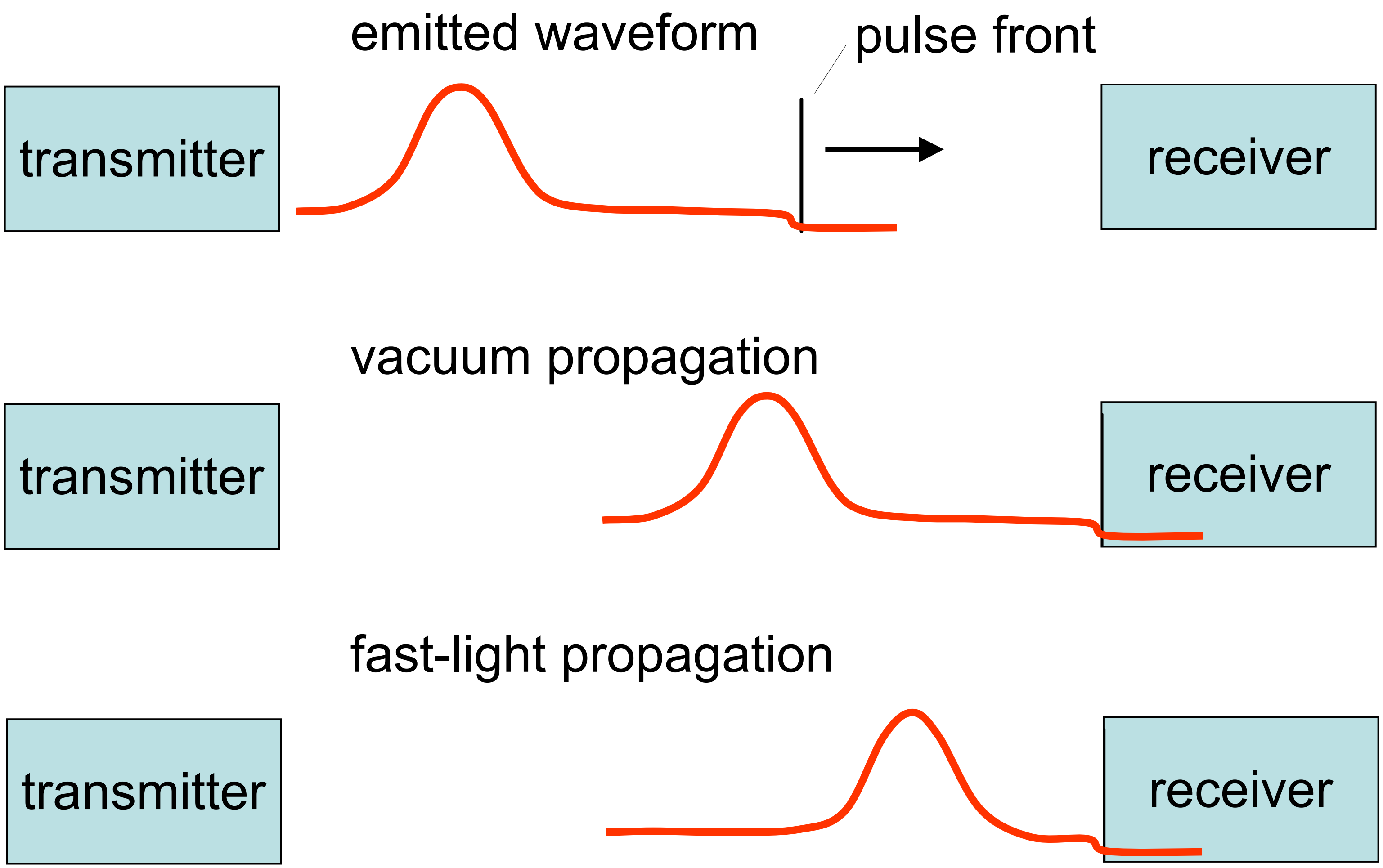
Discontinuity propagates at phase velocity

Information resides in points of discontinuity

Bigelow, Lepeshkin, Shin, and Boyd, J. Phys: Condensed Matter, 3117, 2006.

See also Stenner, Gauthier, and Neifeld, Nature, 425, 695, 2003.

How to Reconcile Superluminality with Causality



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

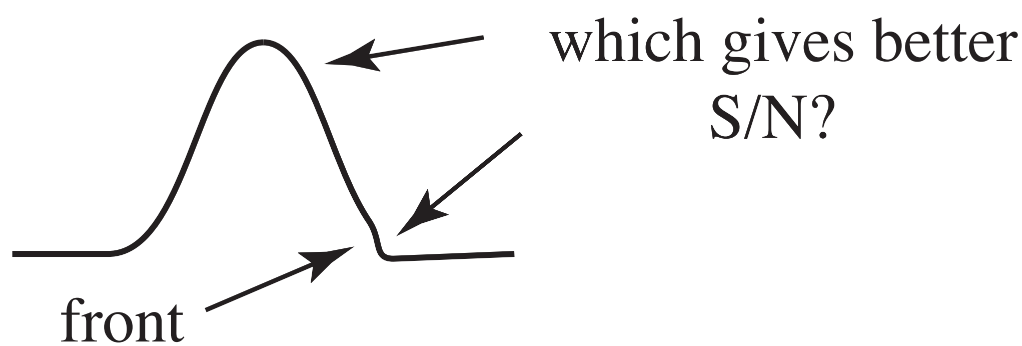
Information Velocity – Tentative Conclusions

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.



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?**

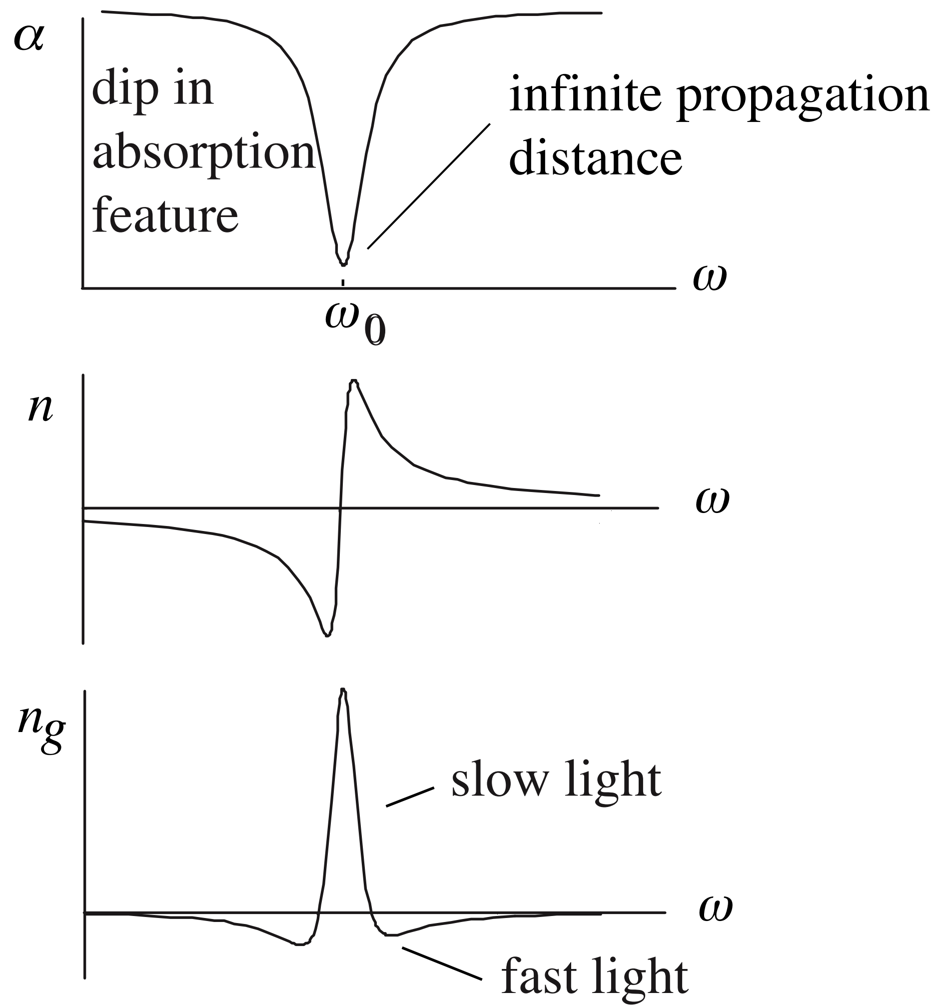
* Boyd, Gauthier, Gaeta, and Willner, PRA 2005

** 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?

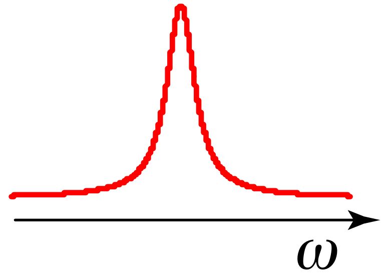
At the bottom of the dip in the absorpton, the absorption can in principle be made to vanish. There is then no limit on how long a propagation distance can be used.

This “trick”works only for slow light.

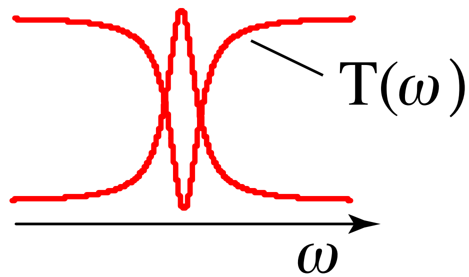


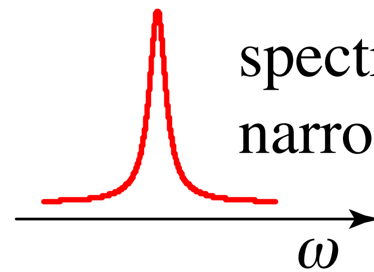
Influence of Spectral Reshaping
(Line-Center Operation, Dip in Gain or Absorption Feature)

input pulse



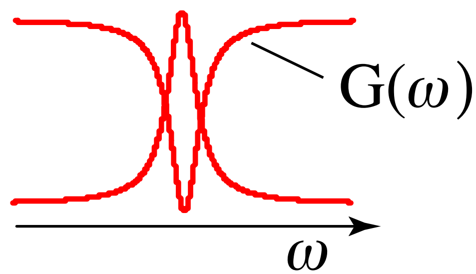
output pulse
slow-light

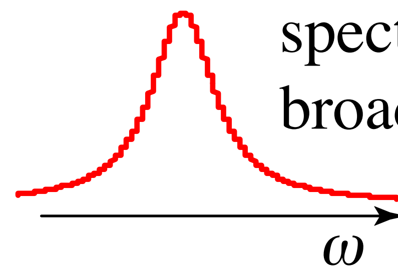




spectrally
narrowed pulse

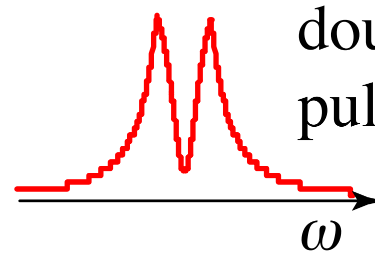
output pulse
fast-light





spectrally
broadened pulse

for still longer propagation distances, the pulse breaks up spectrally and temporally



double-humped
pulse

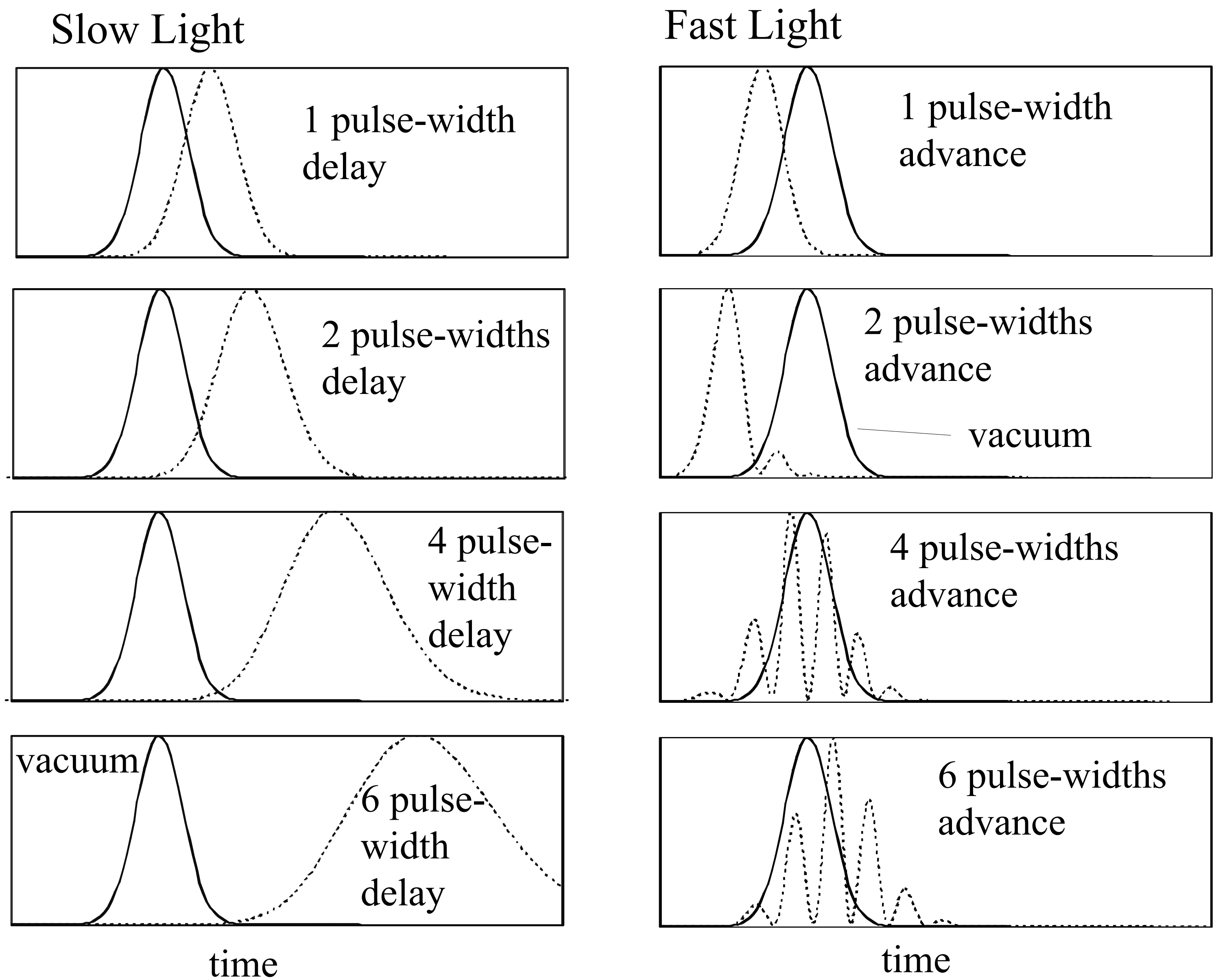
Numerical Results: Propagation through a Linear Dispersive Medium

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

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

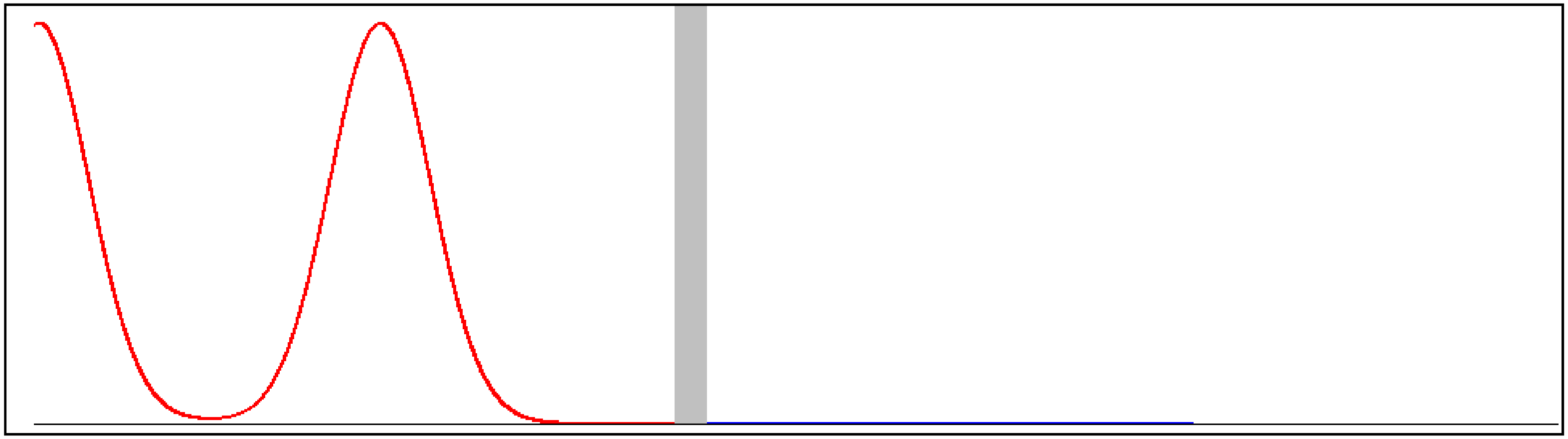
Slow light:
Lorentzian gain line
T = exp(+32)
vary line width to control delay

Same Gaussian input pulse in all cases

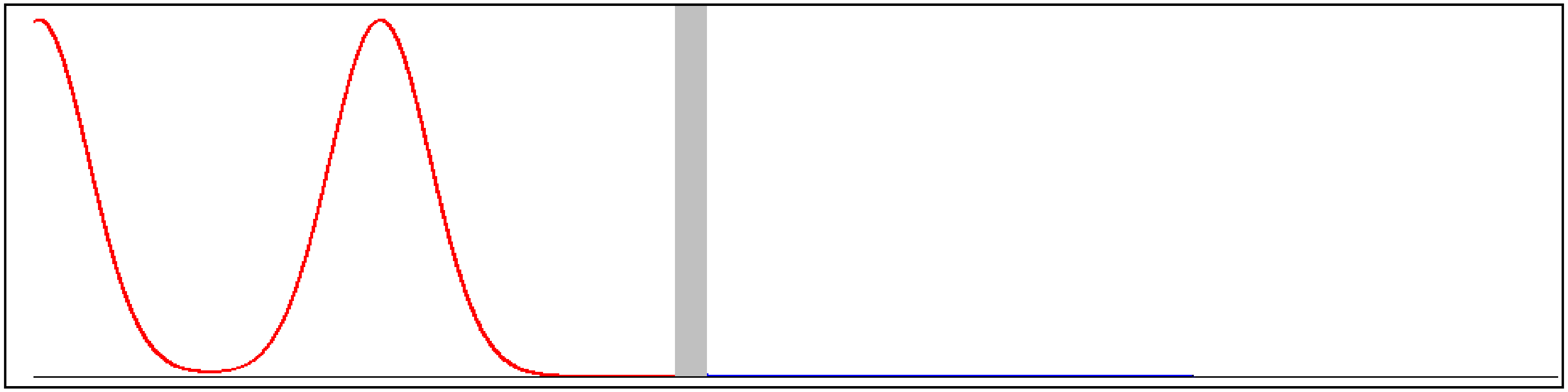


Propagation of Full and Truncated Pulse Trains

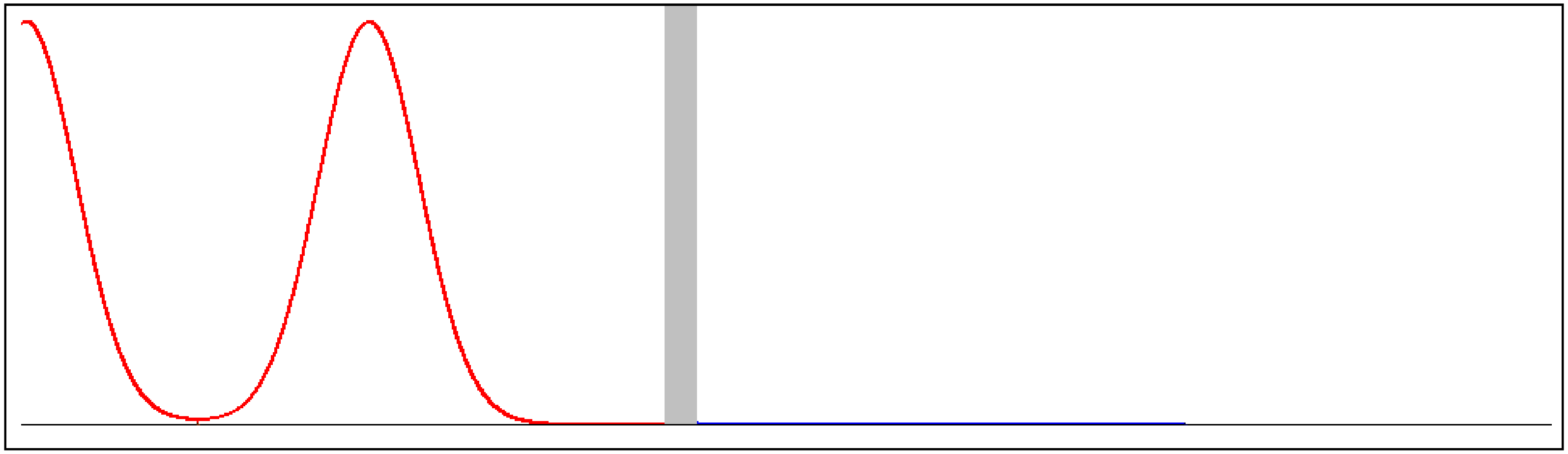
Slow



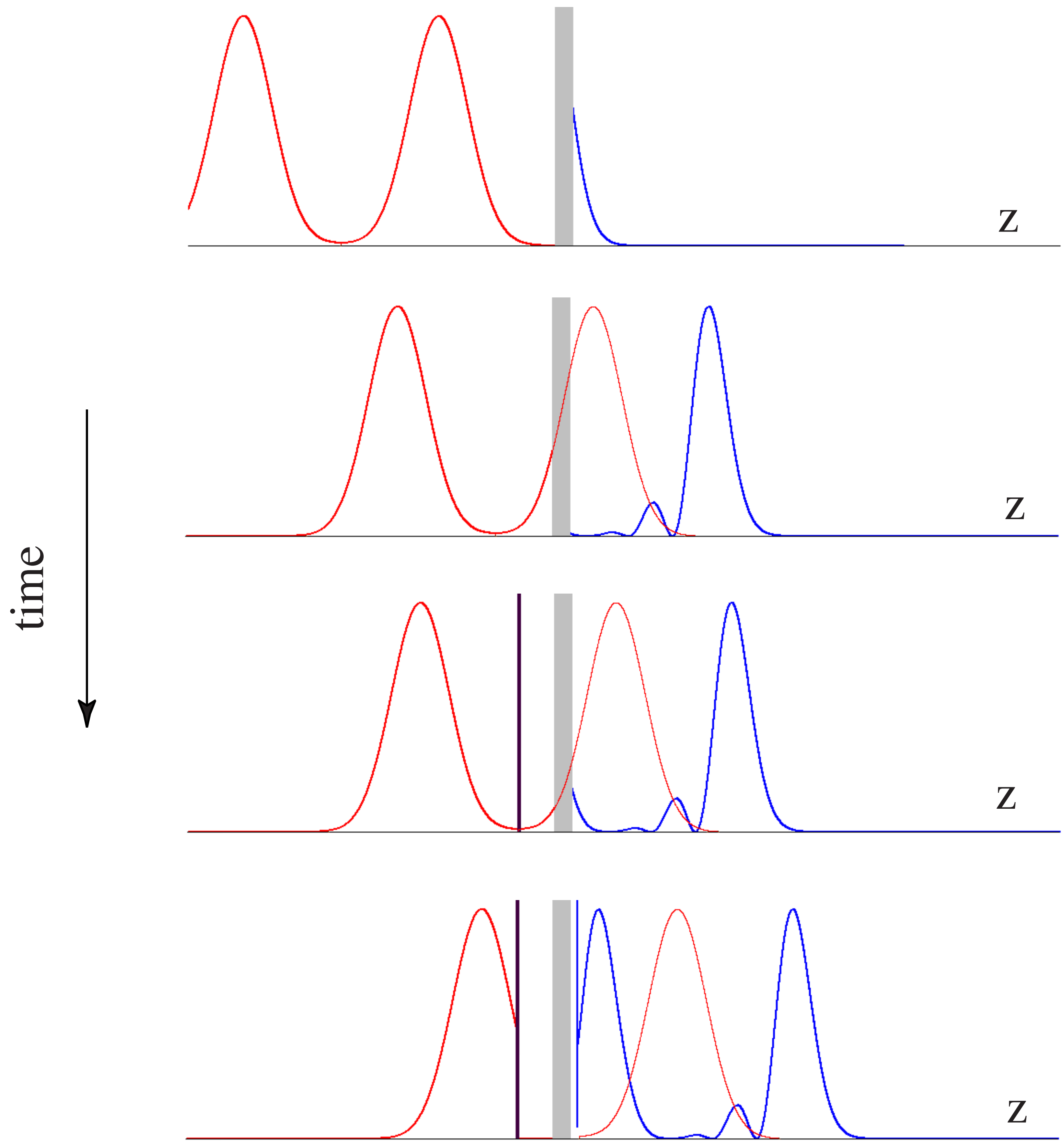
Fast



Fast - truncated



Propagation of Truncated Pulse Trains Through a Fast-Light Medium

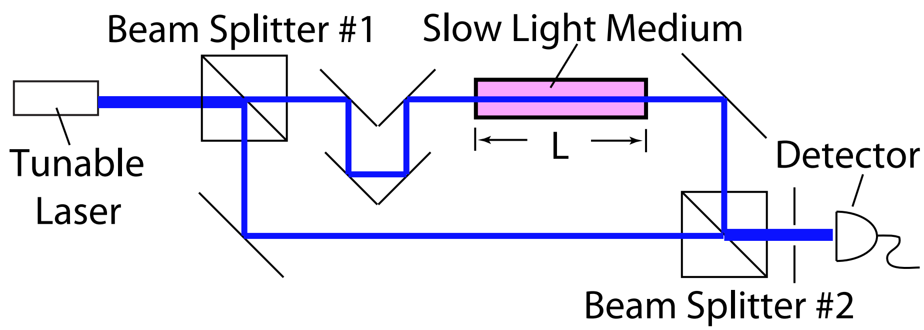


Second output pulse is generated out of "nothing."

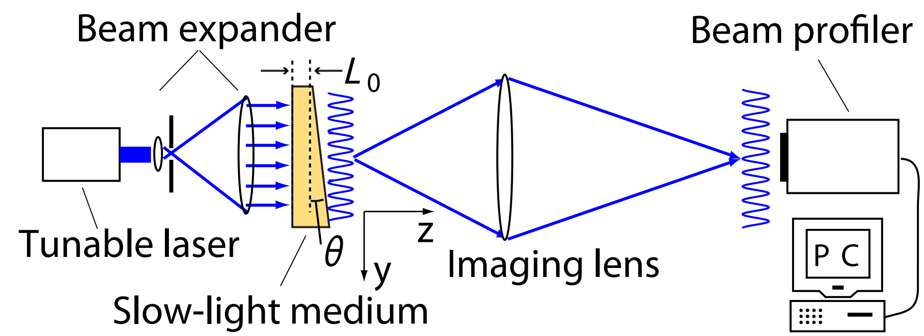
Interferometry and Slow Light

- 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

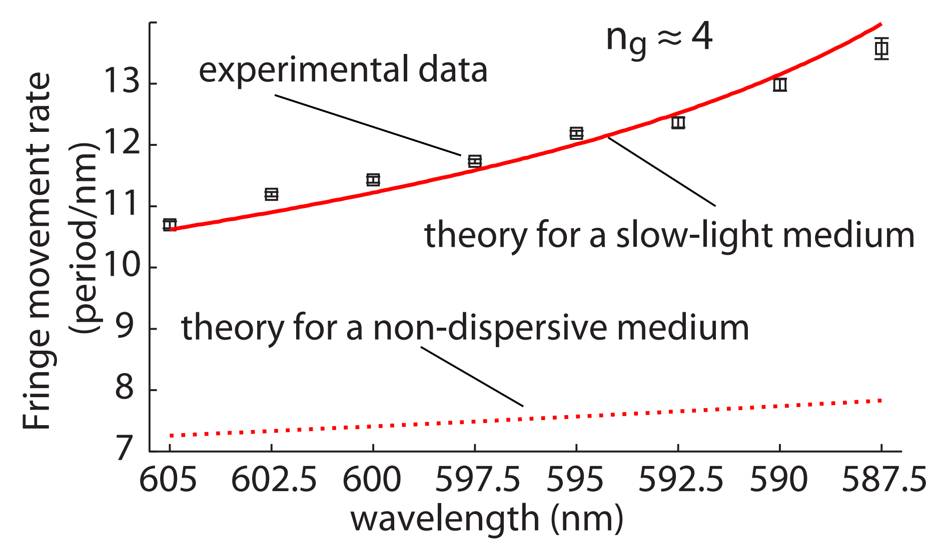


Here is why it works:

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

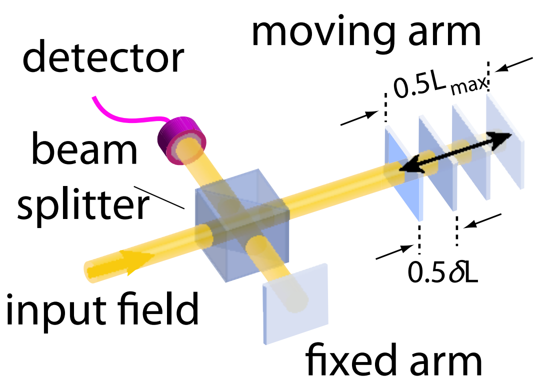
Shih et al, Opt. Lett. 2007

Our experimental results

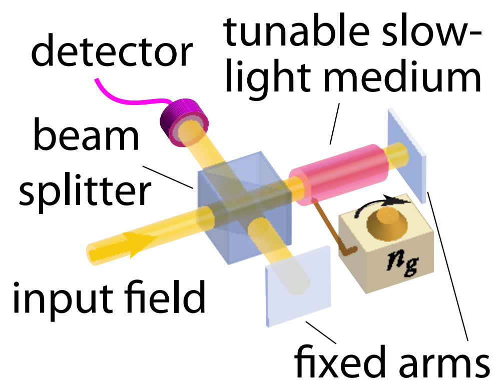


High-Resolution Slow-Light Fourier Transform Interferometer

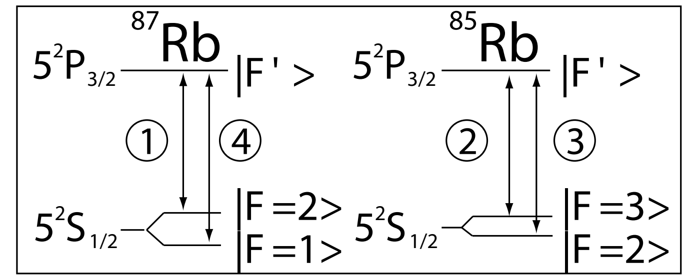
Conventional FT Interferometer



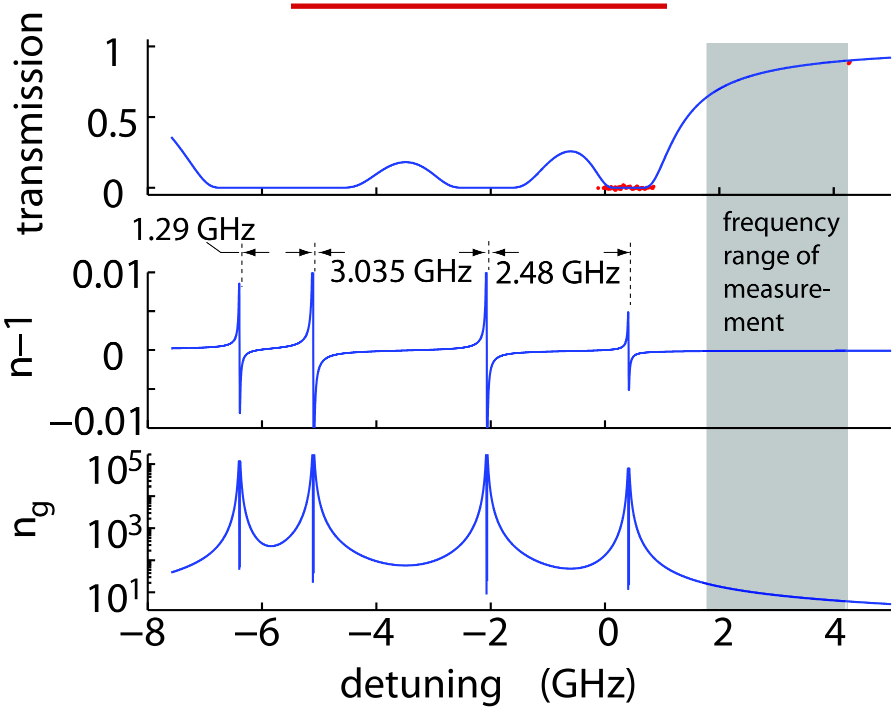
Slow-light FT Interferometer



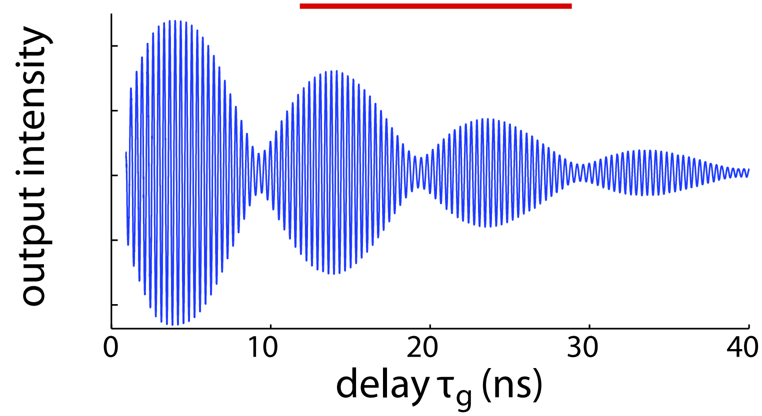
Energy Levels

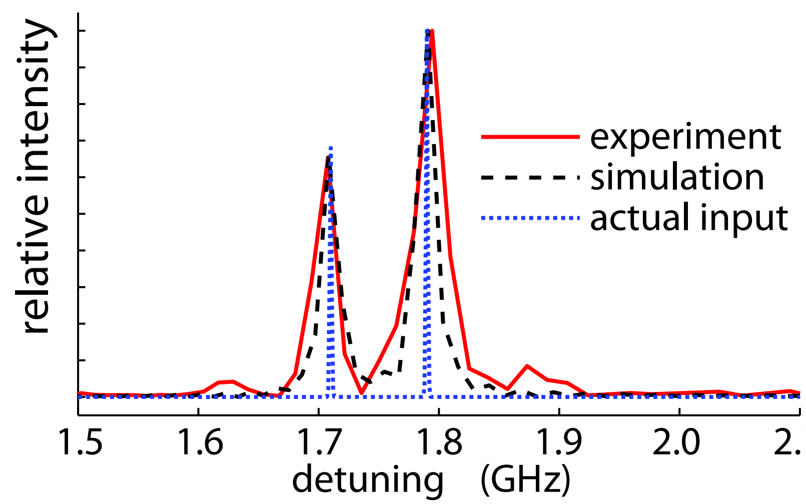


Theoretical Model



Results

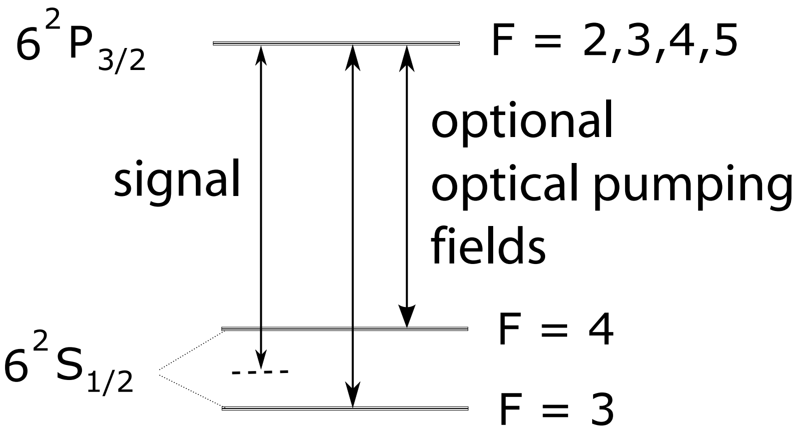




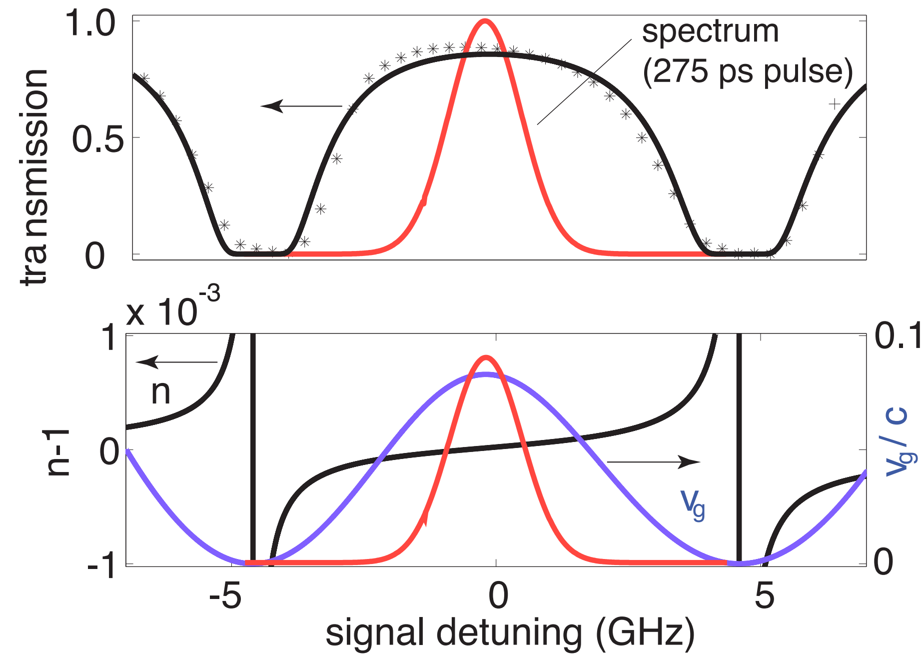
Shi, Boyd, Camacho, Setu, and Howell

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

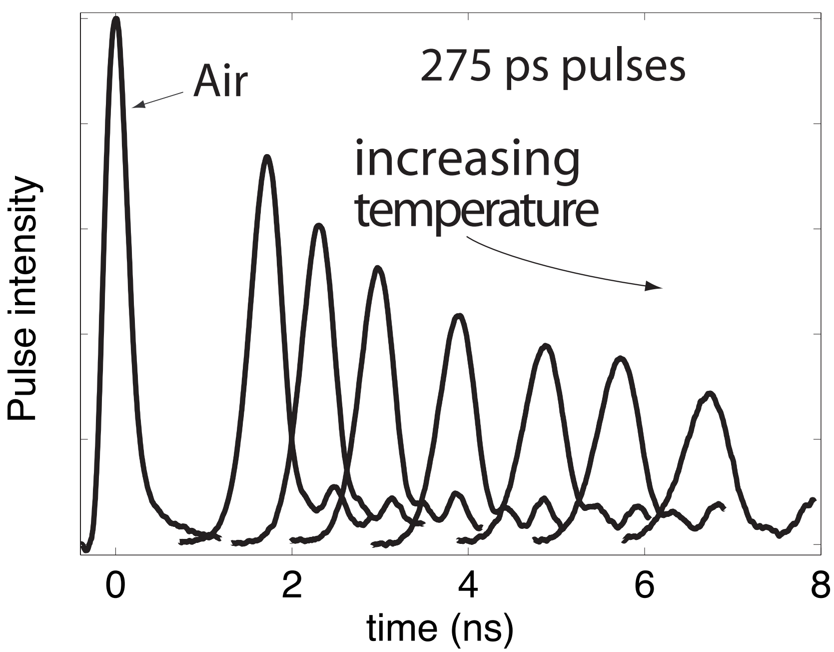
There is no delay-bandwidth product limitation on slow light!



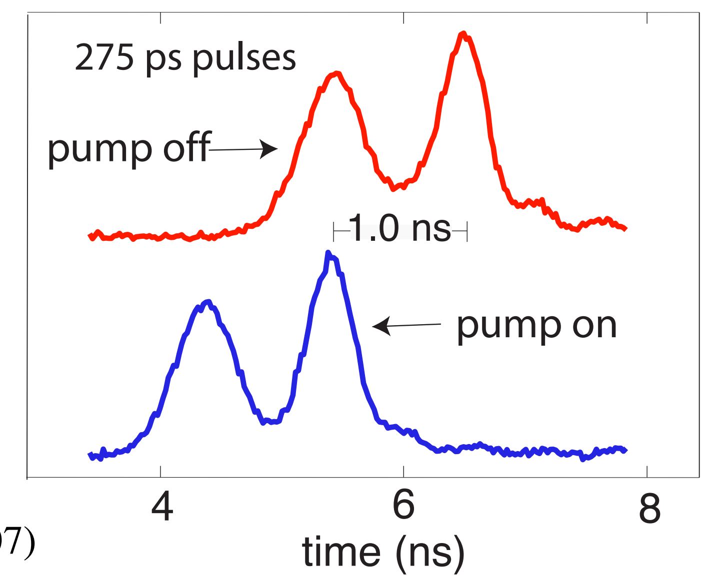
group index approximately 10 to 100



• coarse tuning: temperature

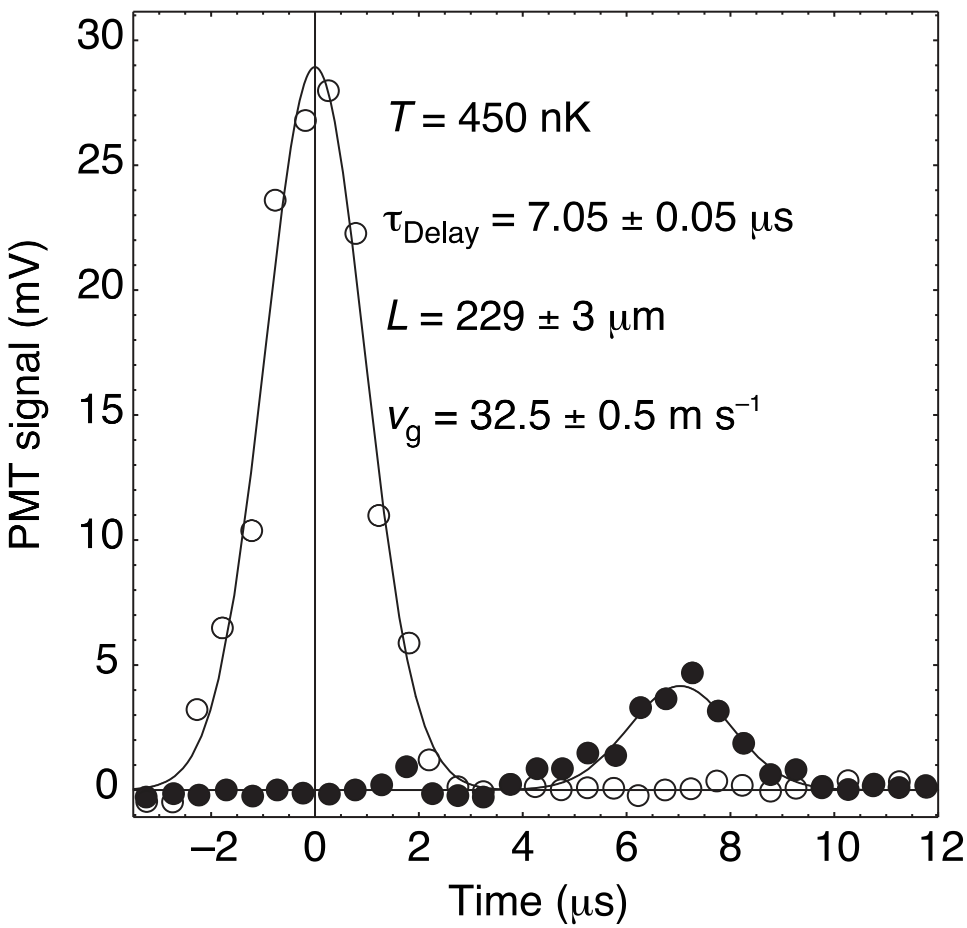


• fine tuning: optical pumping

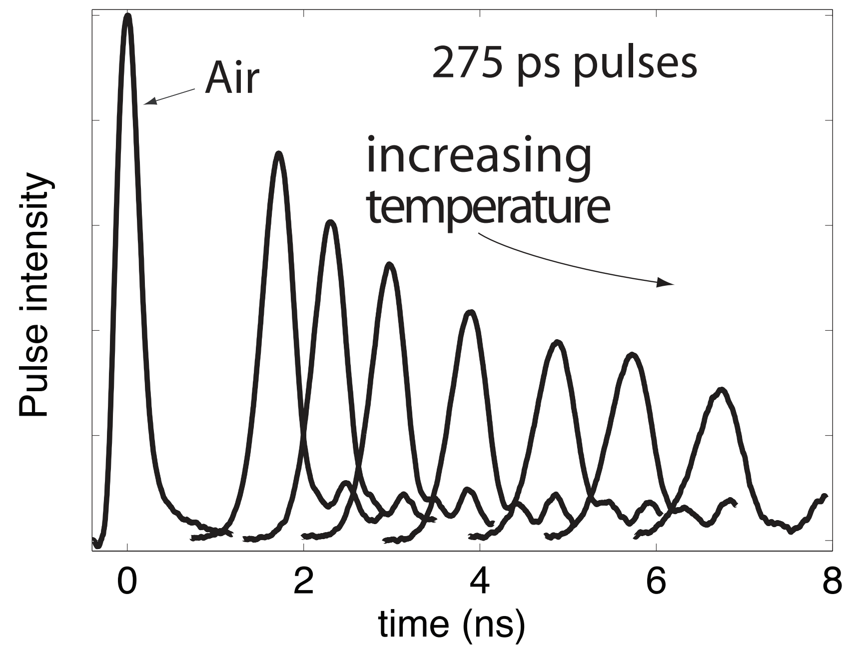


Camacho, Peck, Howell, Schweinsberg, Boyd, PRL 98, 153601 (2007)

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!

Special Thanks to My Students and Research Associates