Slow, Fast, and Backwards Light Propagation in Erbium-Doped Optical Fibers

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with Robert Boyd, George Gehring, Daniel Gauthier, Giovanni Piredda, Paul Narum, Aaron Schweinsberg, Zhimin Shi, Joseph Vornehm, Petros Zerom, and many others

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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

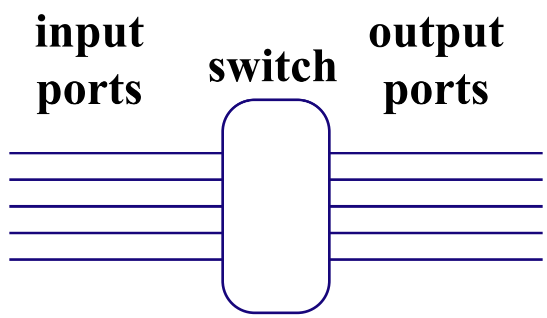
Implications for quantum information

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

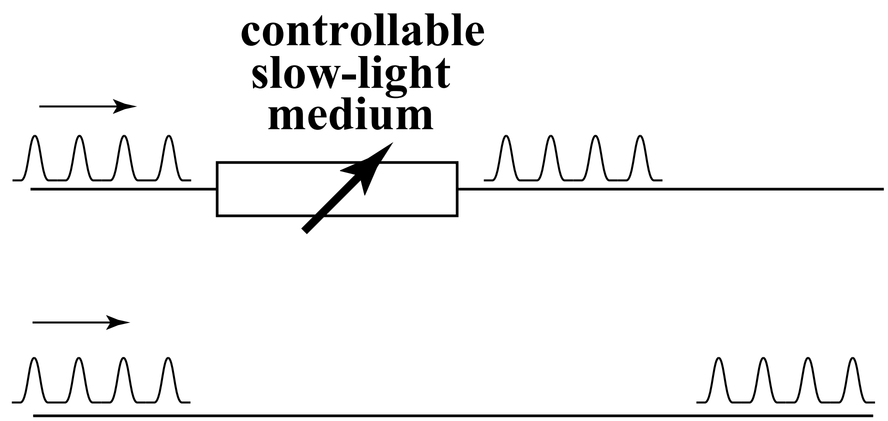
Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.

Slow Light and Optical Buffers

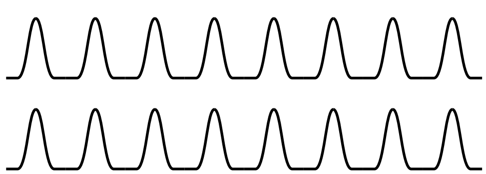
All-Optical Switch



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

Some Approaches to Slow Light Propagation

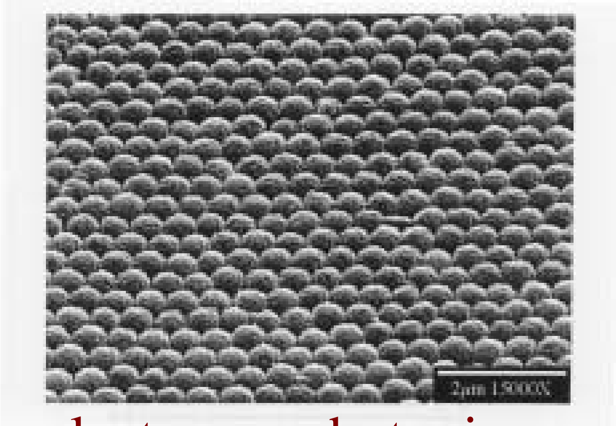
- Use the linear response of atomic systems

  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

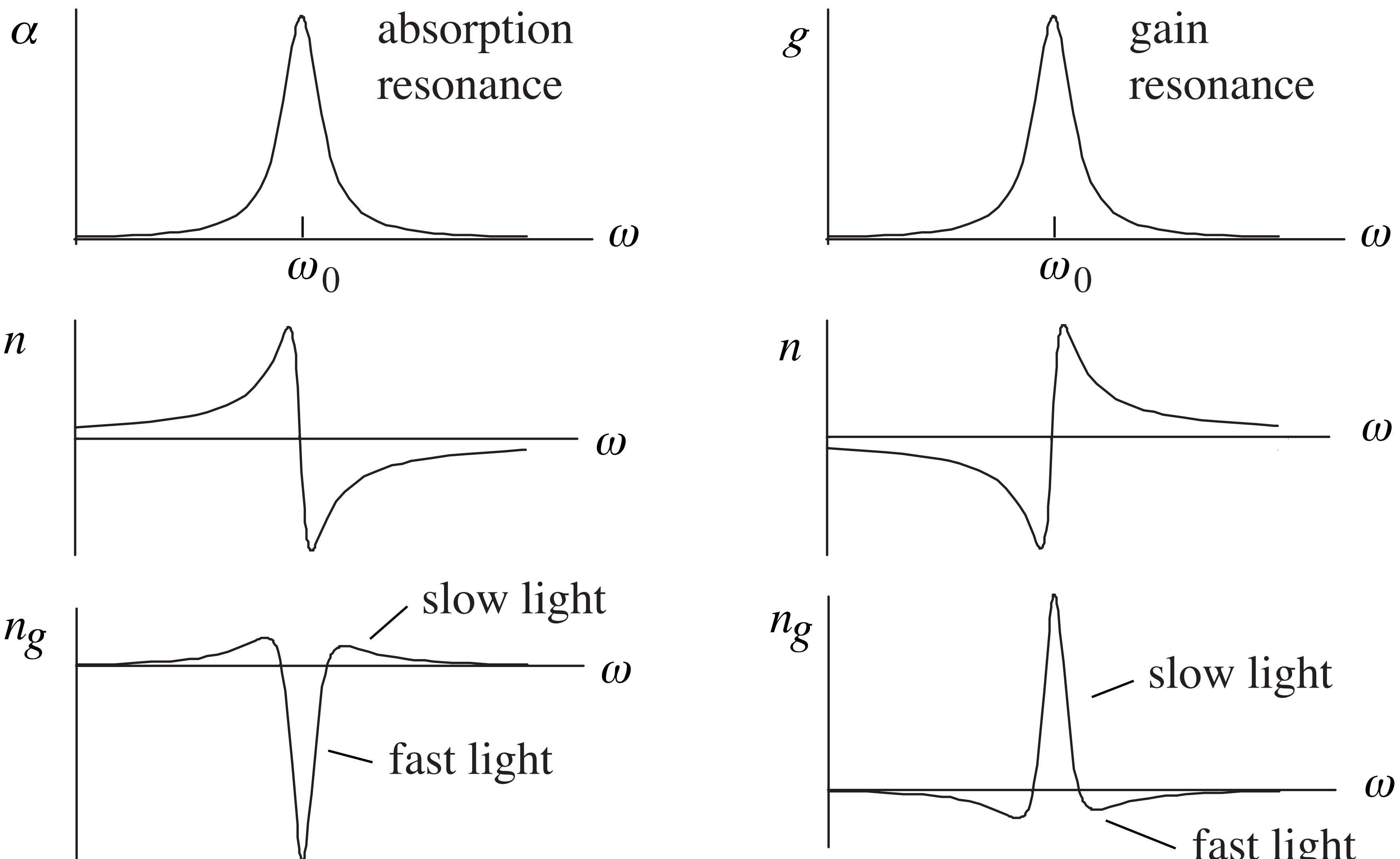
$$v_g = \frac{c}{n_g} \qquad\qquad n_g = n + \omega \frac{dn}{d\omega}$$

Want large dispersion to obtain extreme group velocities

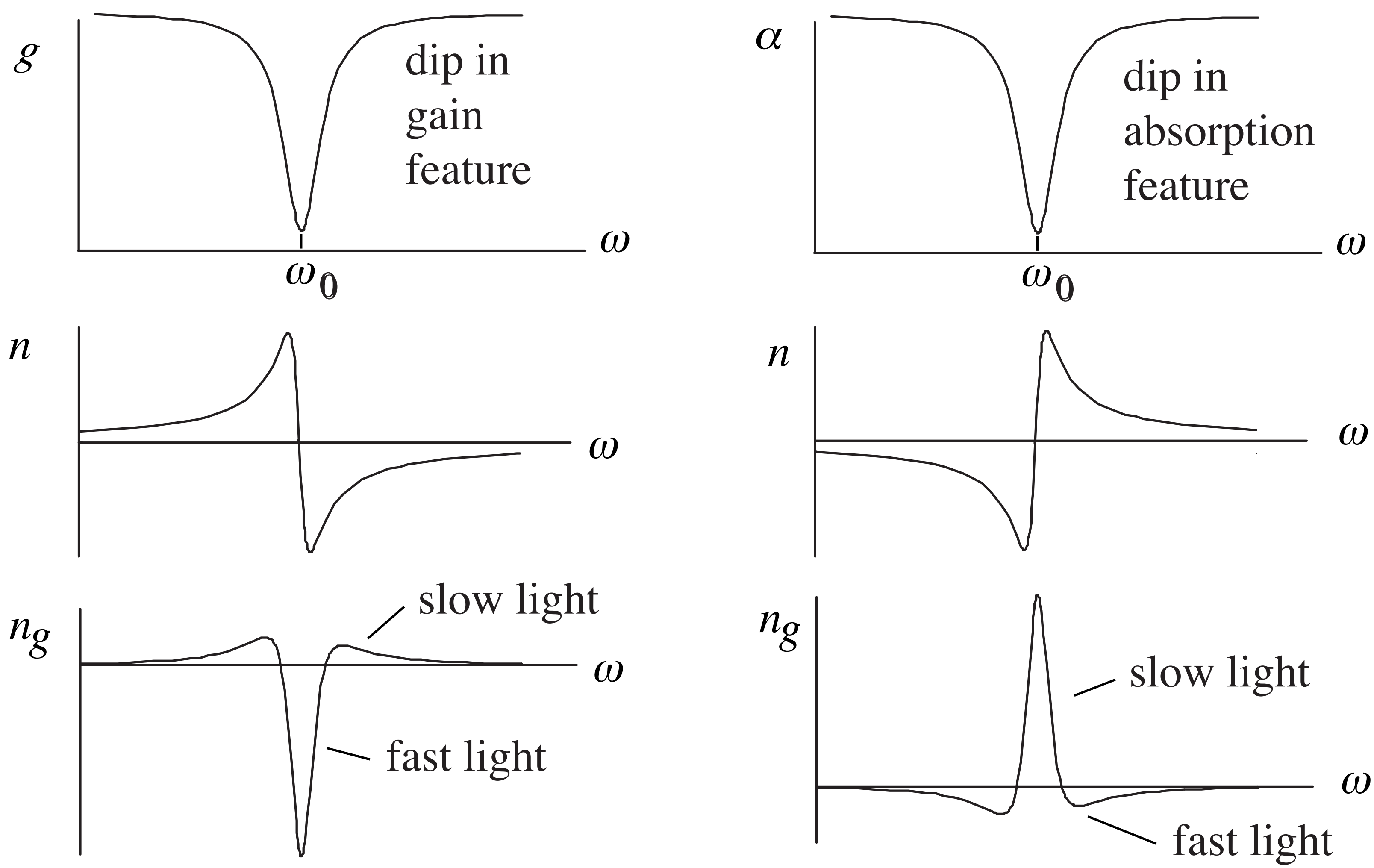
Sharp spectral features produce large dispersion.

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.

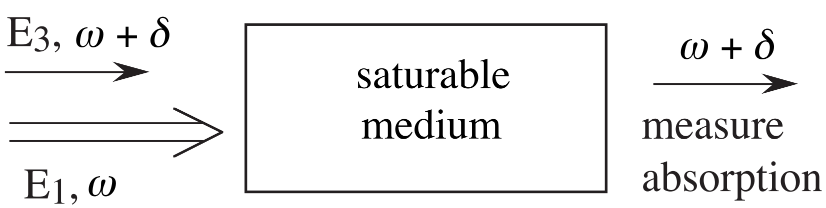
Challenge / Goal   (2003)

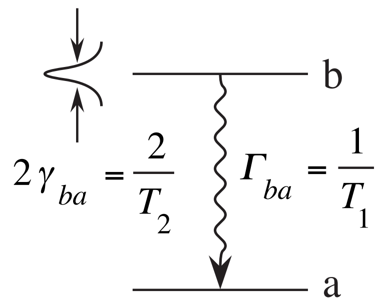
Slow light in a room-temperature, solid-state material.

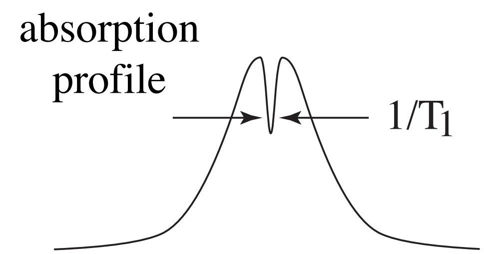
Our solution:

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)

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.

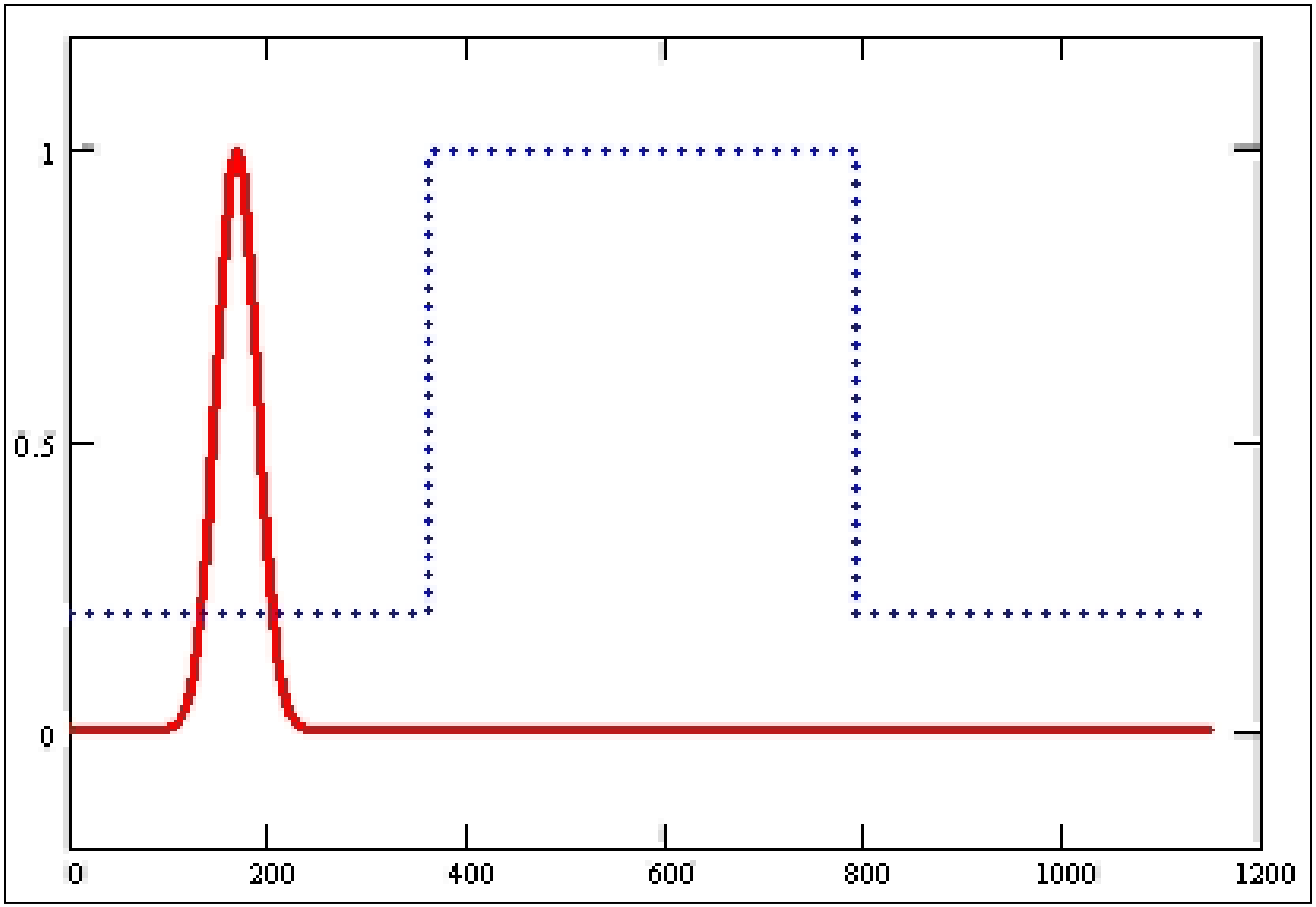
Study three cases:

Slow light $v_g = 0.5\ c$

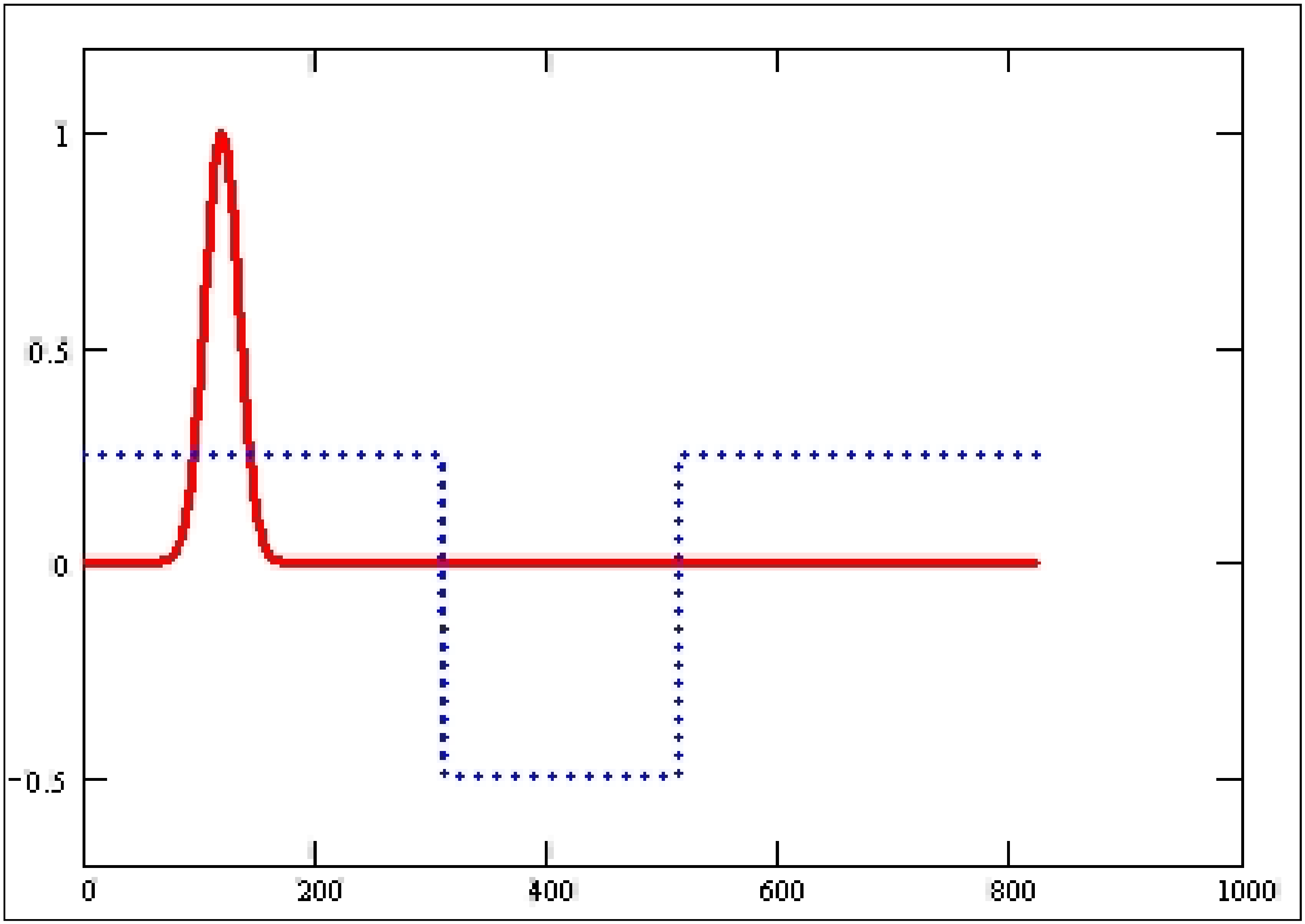
Fast light $v_g = 5\ c$ and $v_g = -2\ c$

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)

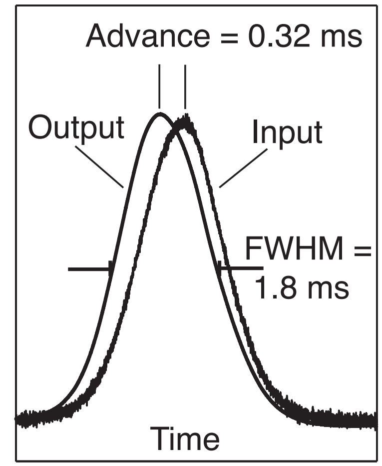


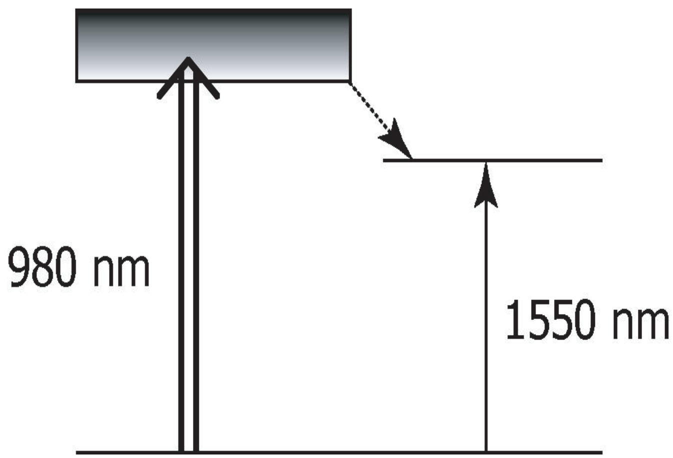
Pulse Propagation through a Backwards-Light Medium ($n_g = -.5$, $v_g = -2\ c$)

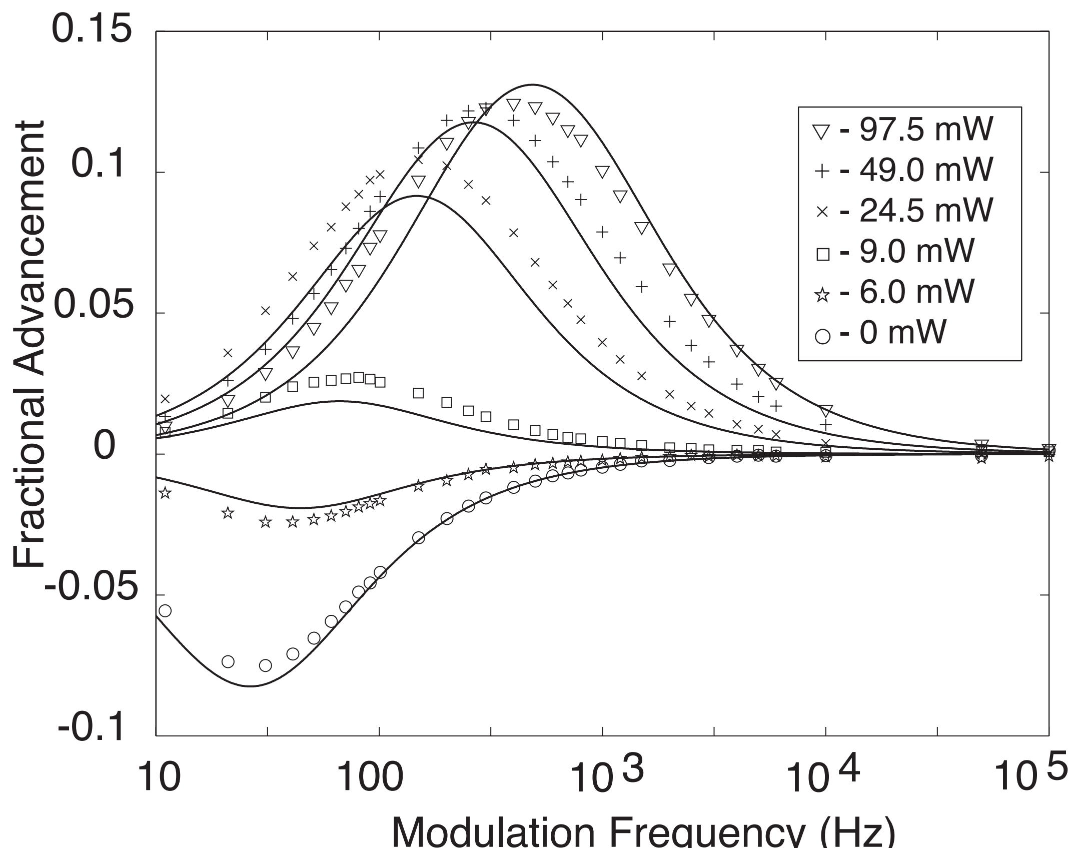


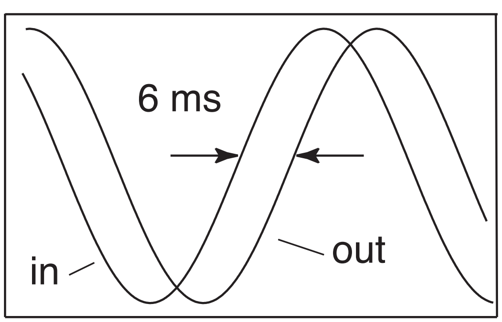
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



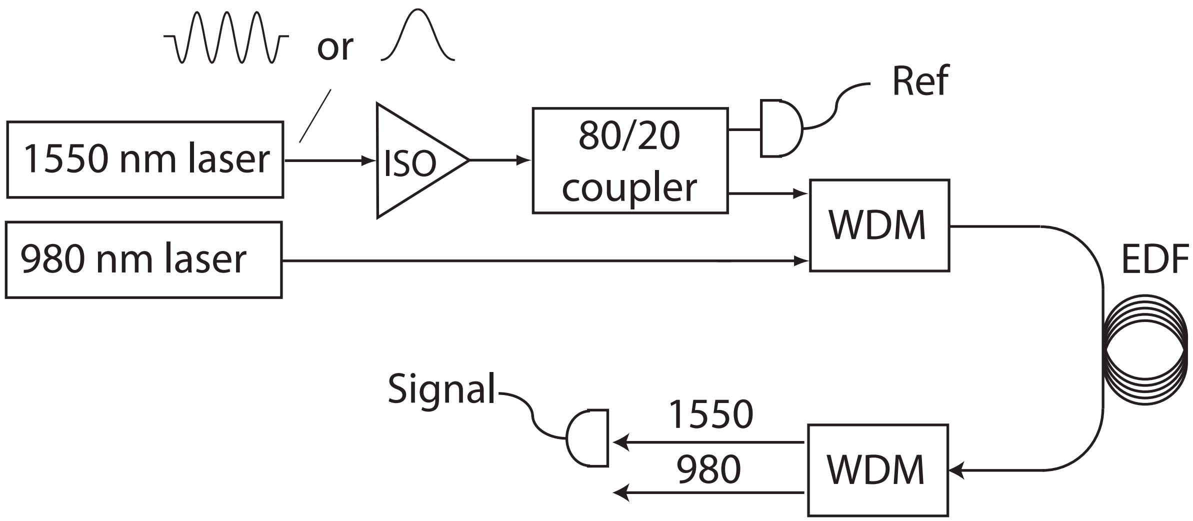






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

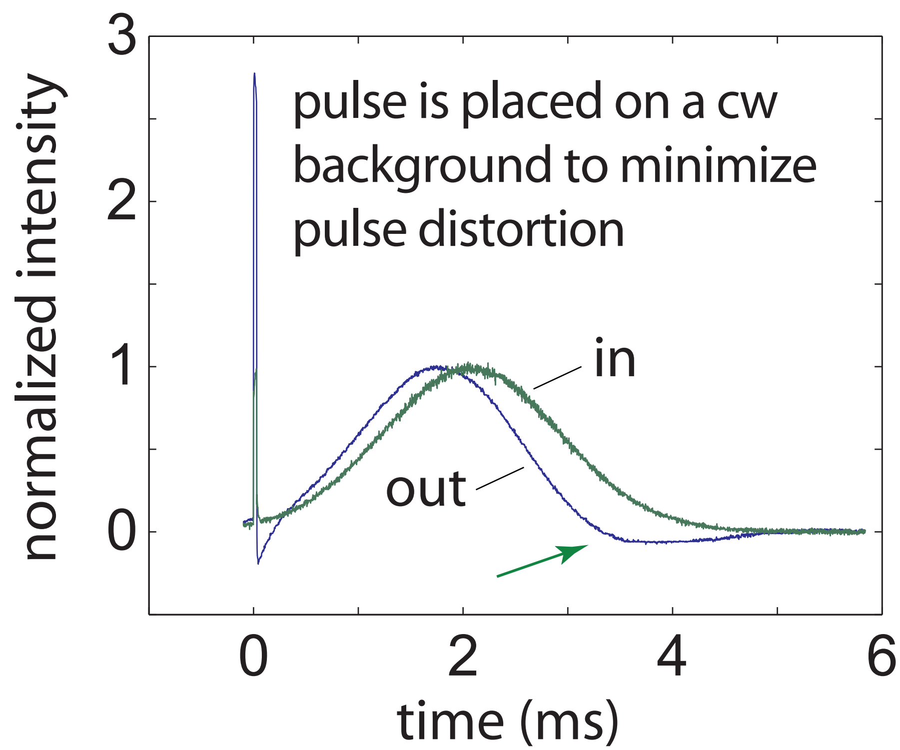
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



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

Procedure

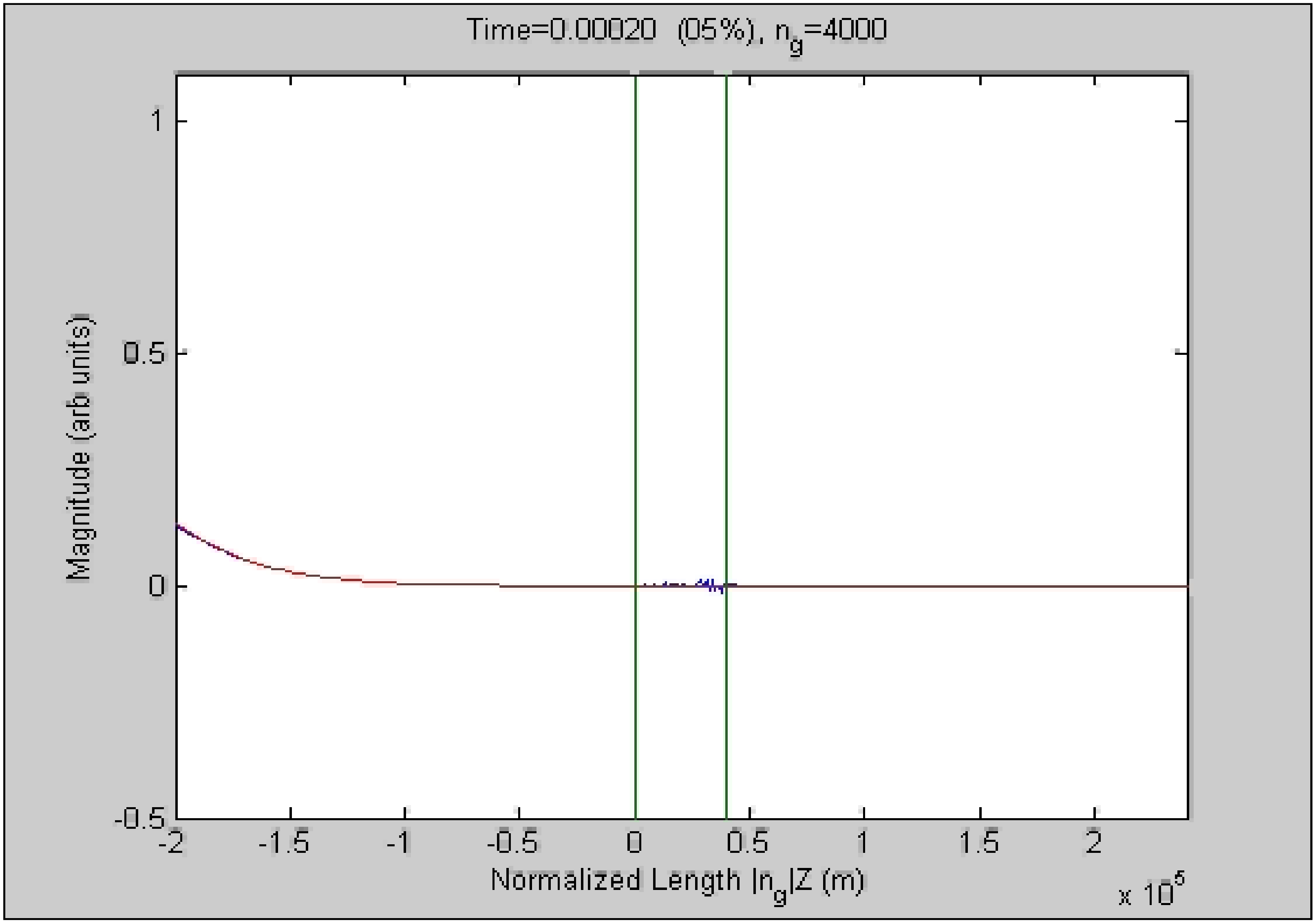
- cutback method
- couplers embedded in fiber



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)



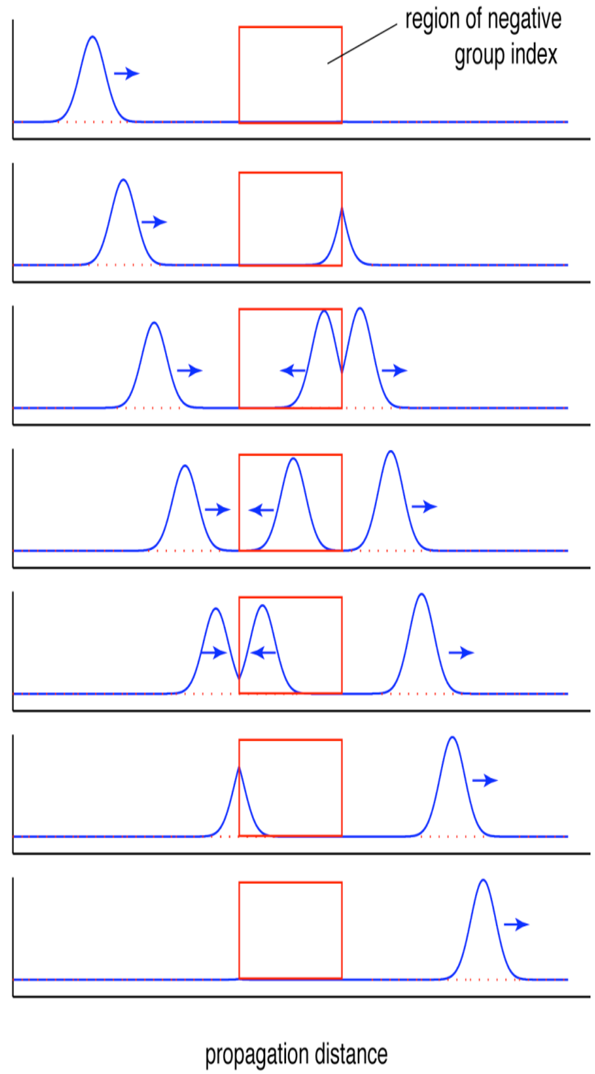
Observation of "Backwards" Pulse Propagation

- A strongly counterintuitive phenomenon

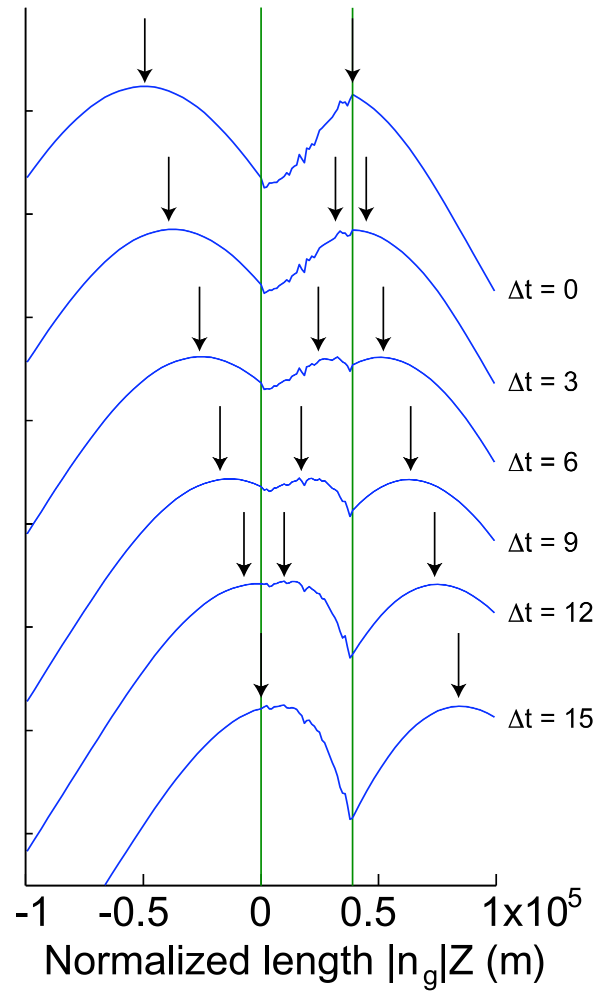
- But entirely consistent with established physics

- 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

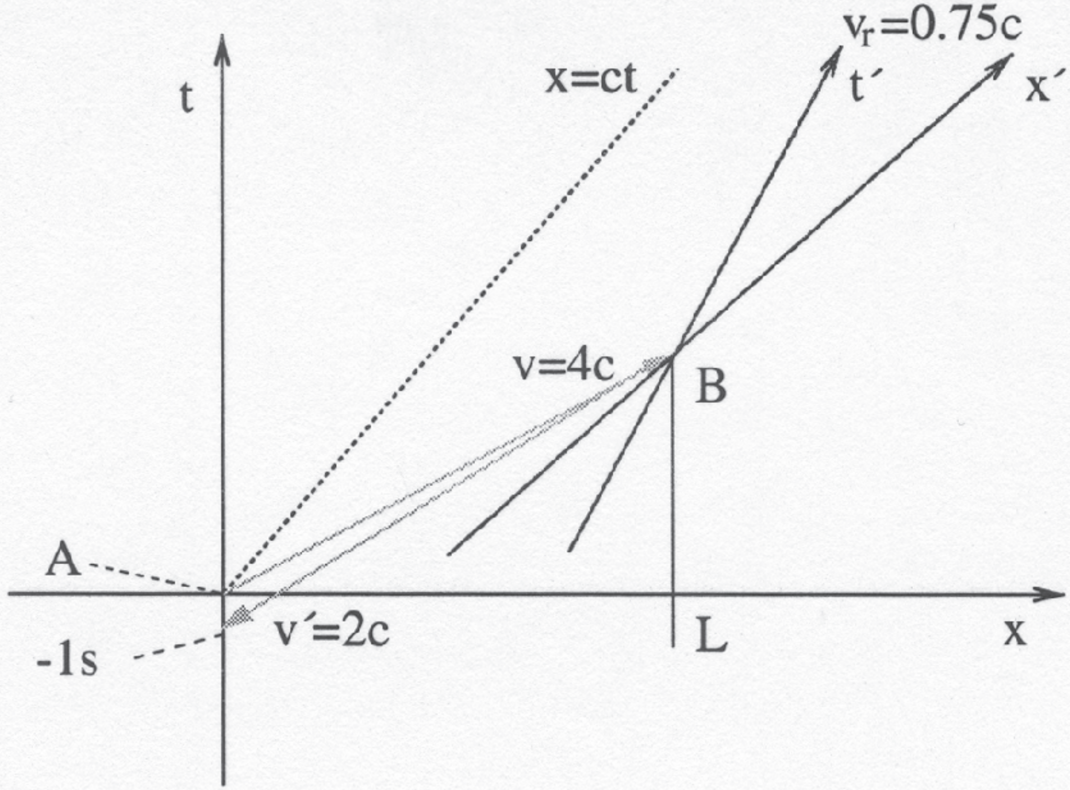
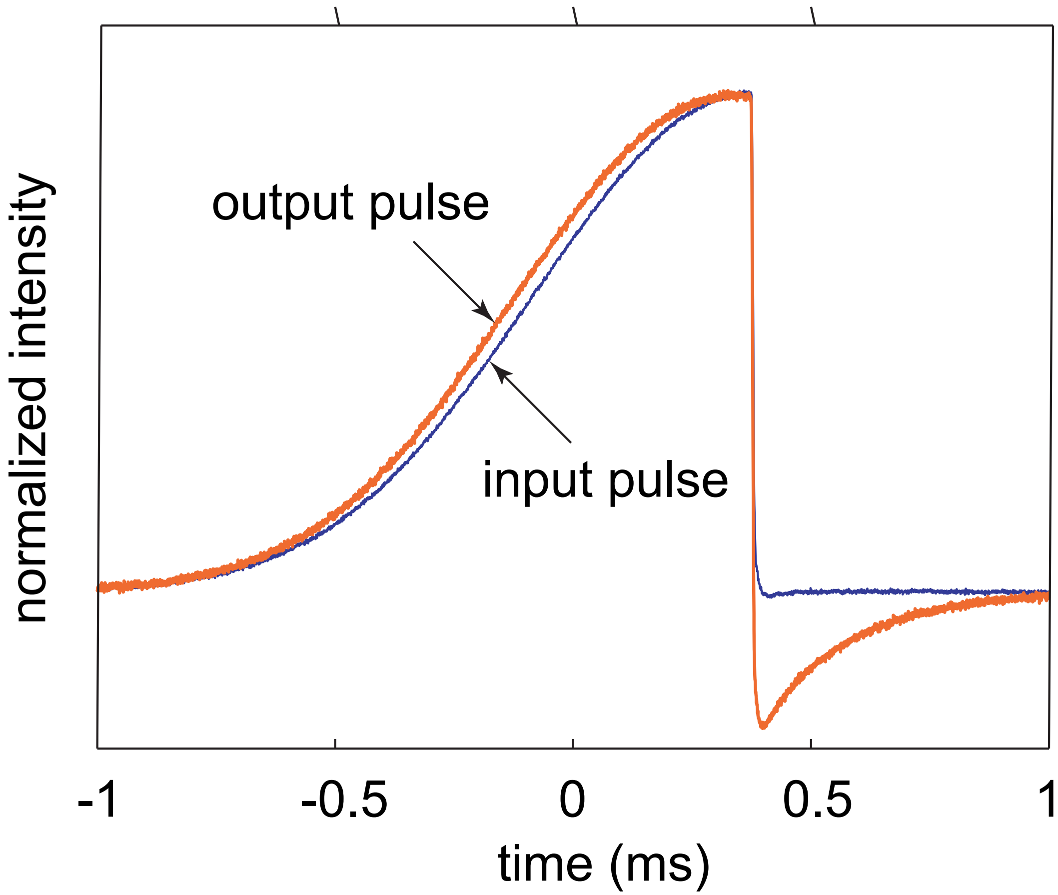


Fig. 6 Coordinates of two inertial observers **A** $(0, 0)$ and **B** with $O(x, t)$ and $O'(x', t')$ moving with a relative velocity of $0.75c$. The distance L between **A** and **B** is 2 000 000 km. **A** makes use of a signal velocity $v_s = 4c$ and **B** makes use of $v_s' = 2c$. The numbers in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

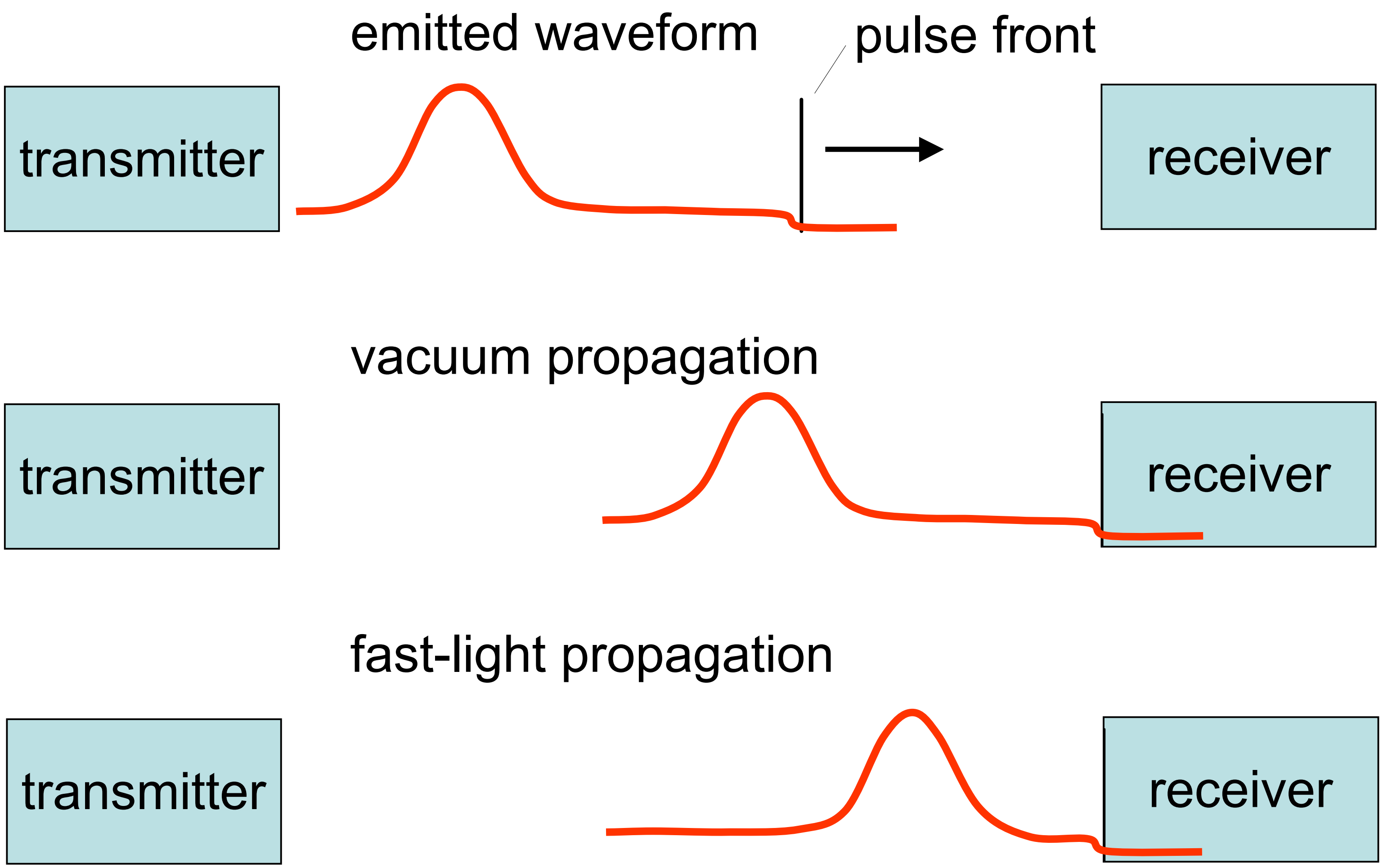
Discontinuity propagates at phase velocity

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.

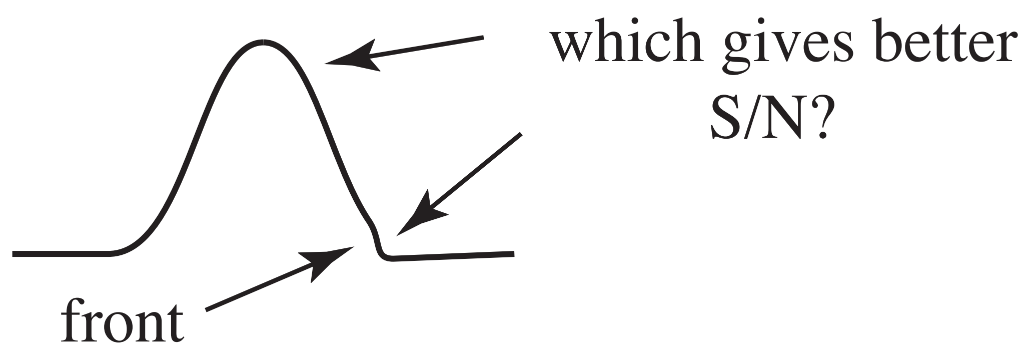
Information Velocity – Tentative Conclusions

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.



Special Thanks to My Students and Research Associates