# Slow, Fast, and “Backwards” Light: Fundamental Aspects

Robert W. Boyd
University of Rochester

Paul Narum
Norwegian Defence Research Establishment

with George Gehring, Giovanni Piredda, Aaron Schweinsberg, Katie Schwertz, Zhimin Shi, Heedeuk Shin, Joseph Vornehm, Petros Zerom.

Presented at PQE, January 6, 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

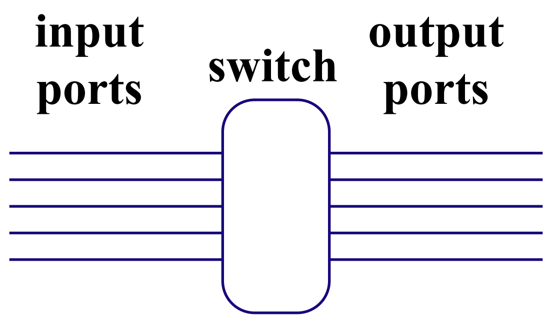
Implications for quantum information

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

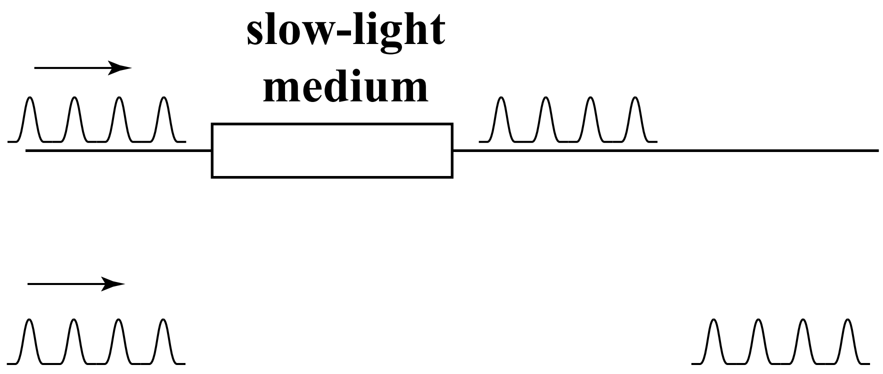
Boyd and Gauthier, “Slow and Fast Light,” in Progress in Optics, 43, 2002.

# Slow Light and Optical Buffers

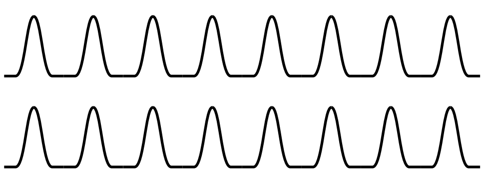
## All-Optical Switch




## 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 and Fast Light and Optical Resonances

Pulses propagate at the group velocity given by

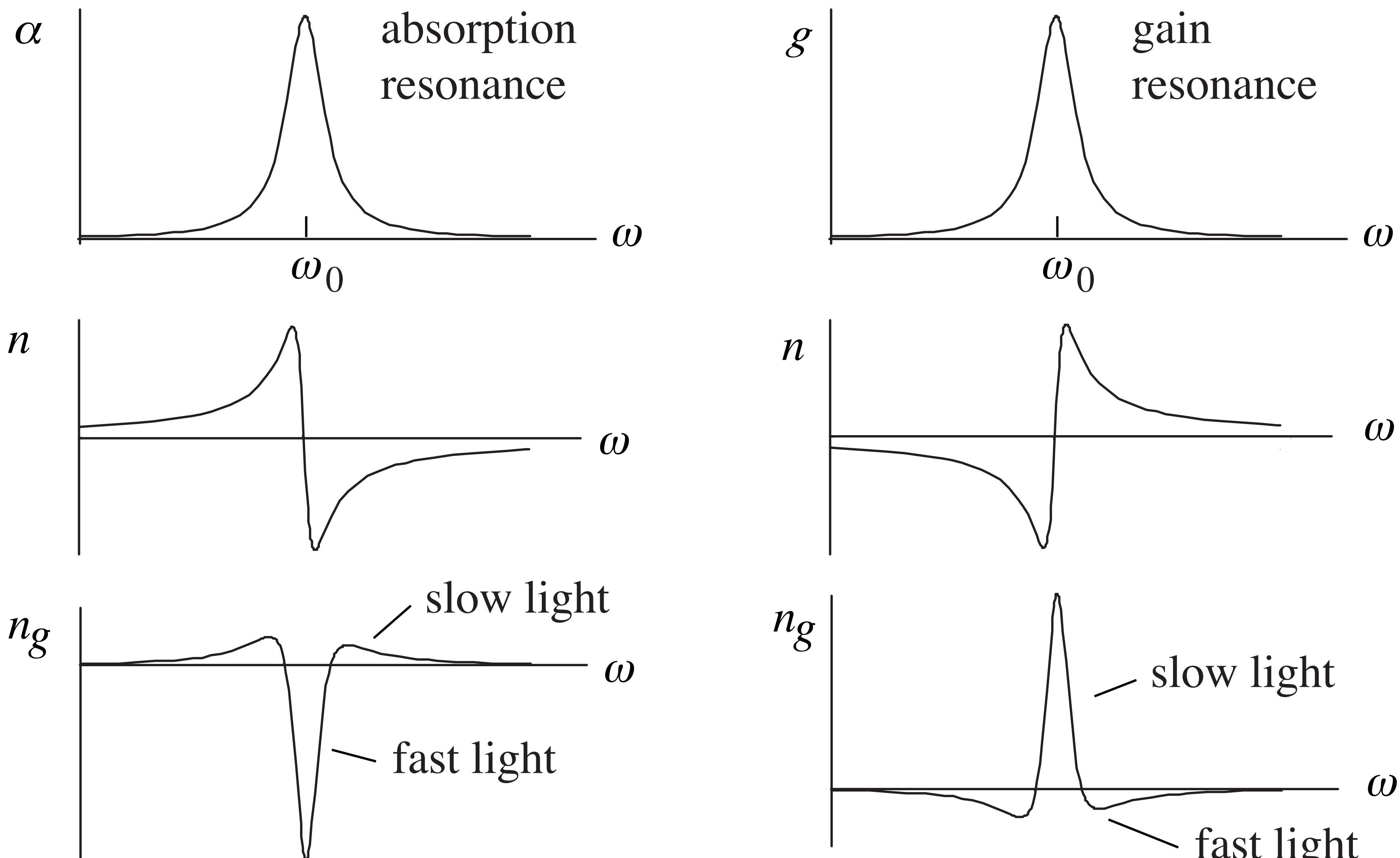
$$v_g = \frac{c}{n_g} \qquad\qquad n_g = n + \omega \frac{dn}{d\omega}$$

Want large dispersion to obtain extreme group velocities

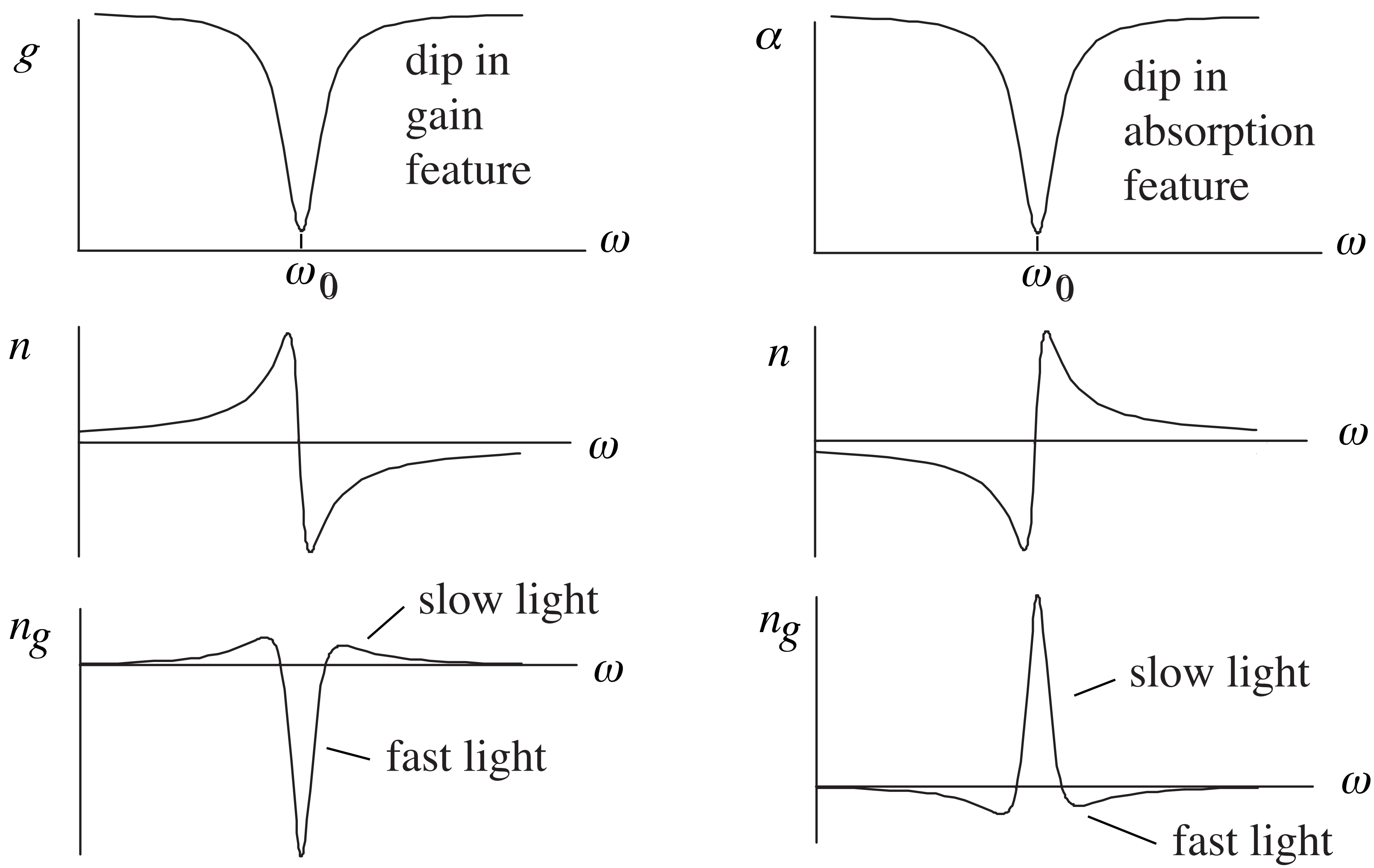
Sharp spectral features produce large dispersion.

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

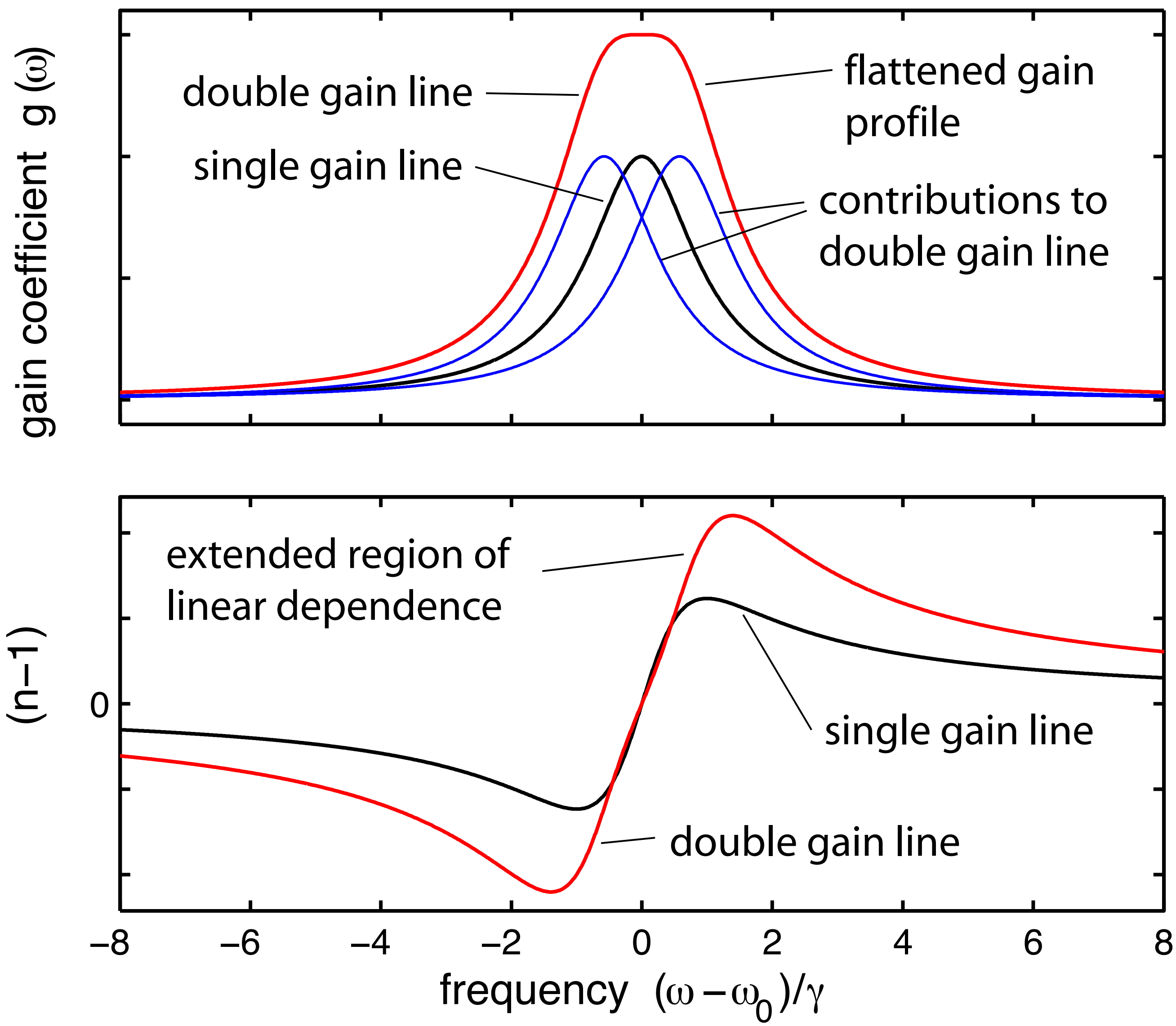


# How to Create Slow and Fast Light II – Use Dip in Gain or Absorption Feature




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).

# 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.

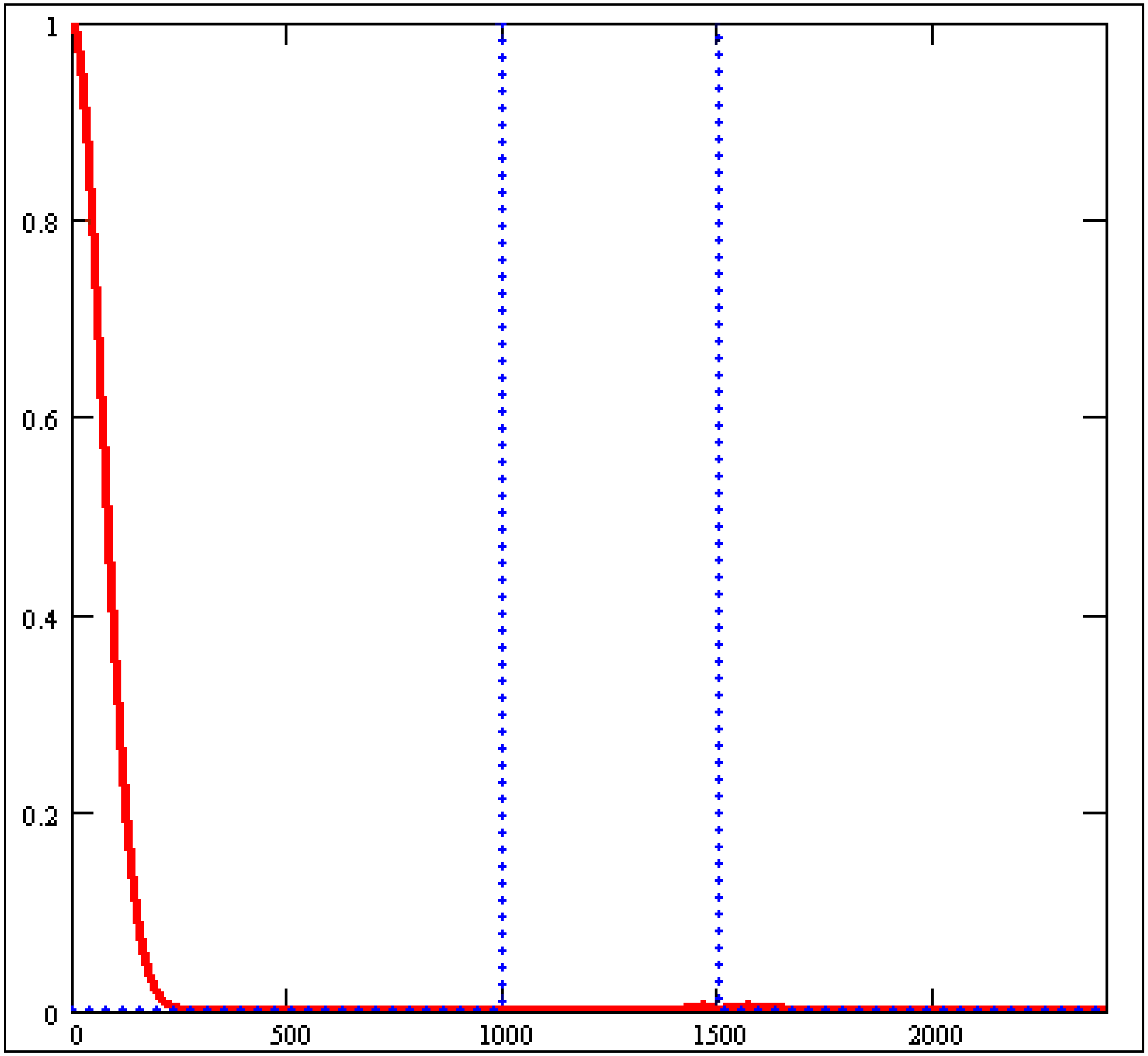
Study three cases:

Slow light $v_g = 0.5\ c$

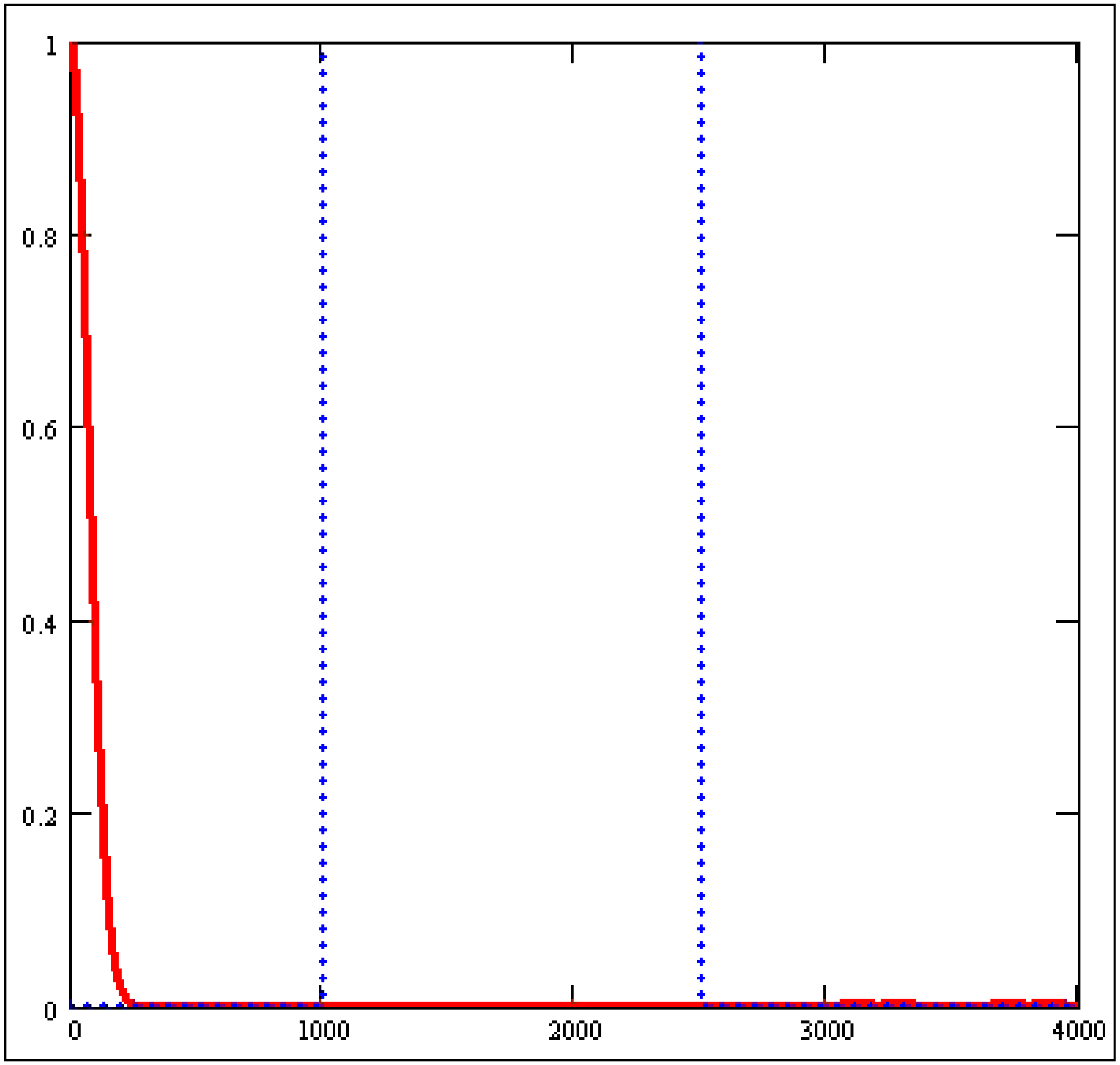
Fast light $v_g = 5\ c$ and $v_g = -2\ c$

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

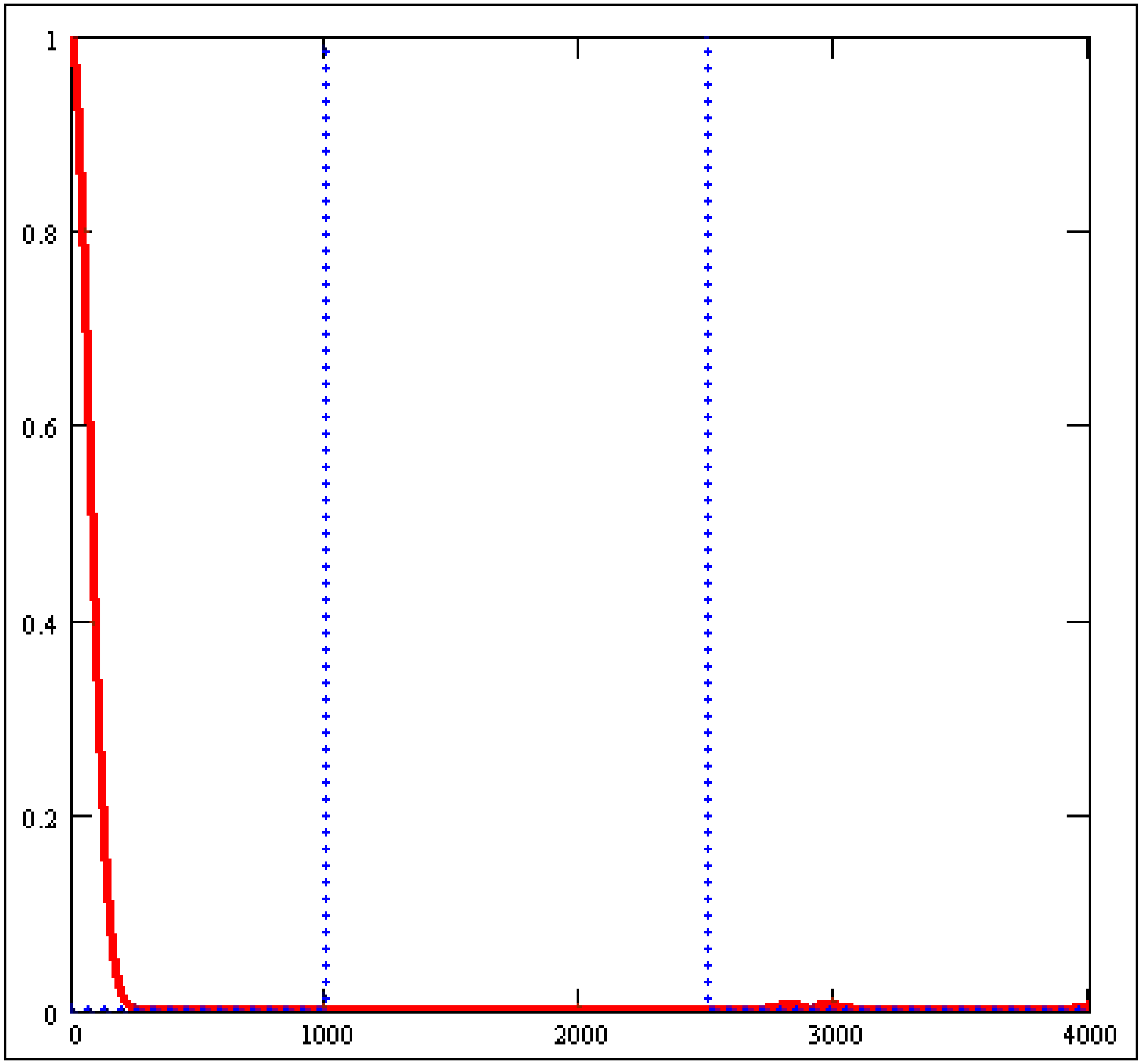
# Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



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

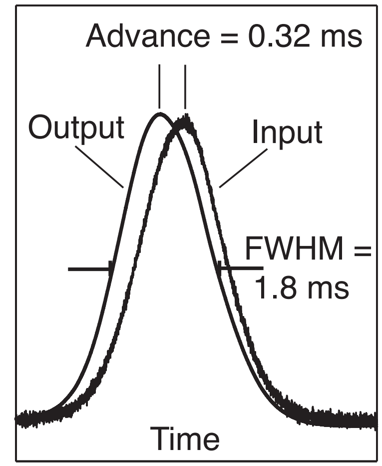


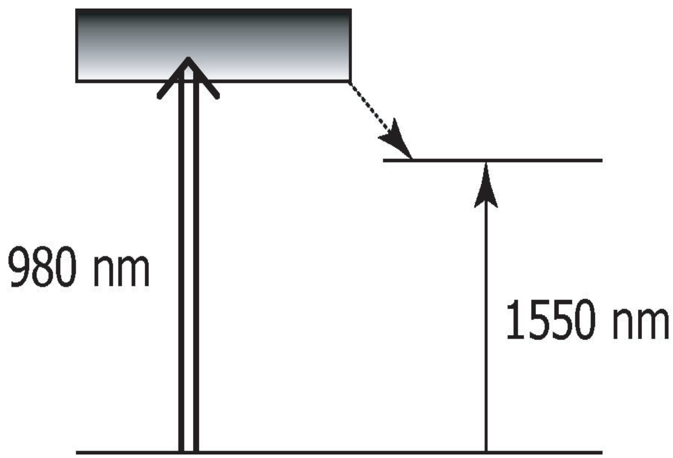
# Pulse Propagation through a Fast-Light Medium ($n_g$ = -.5, $v_g$ = -2 c)

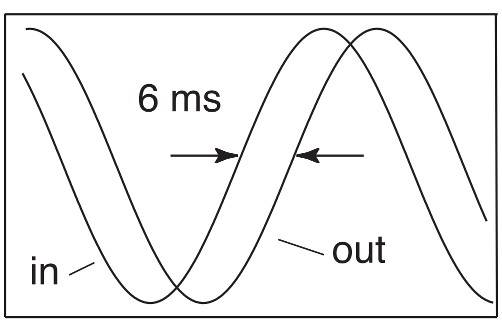


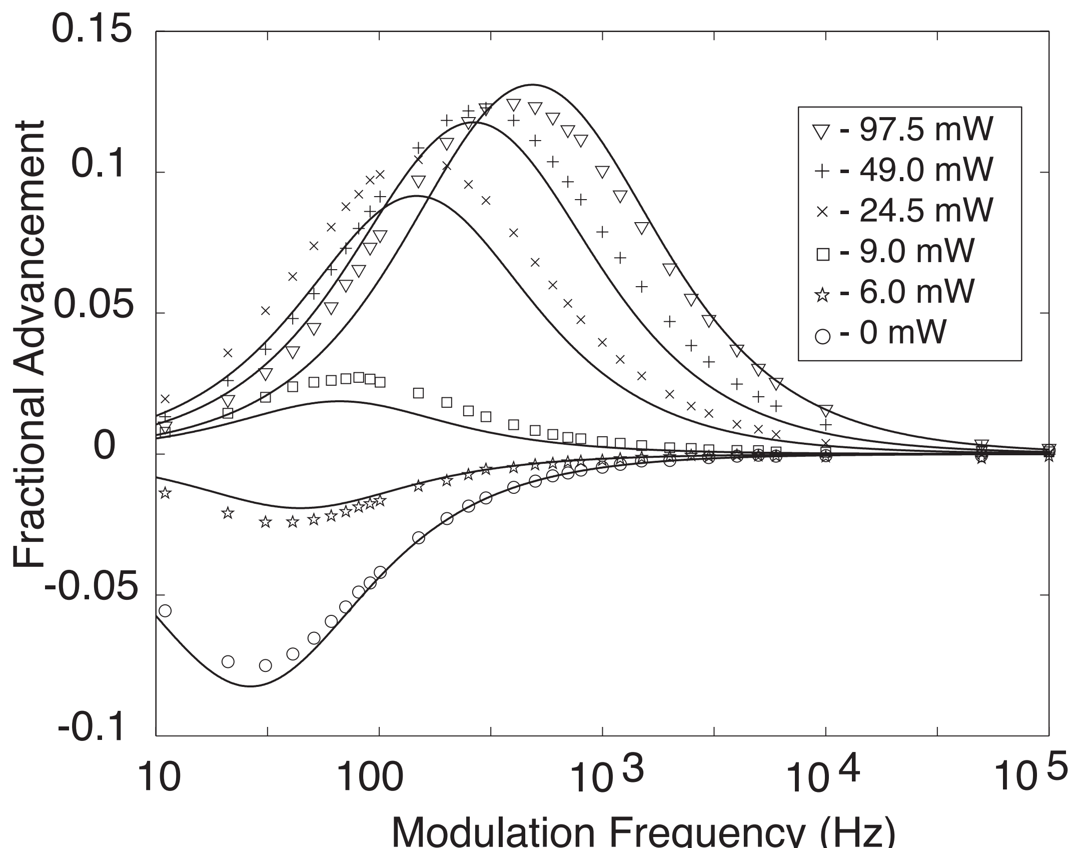
# Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



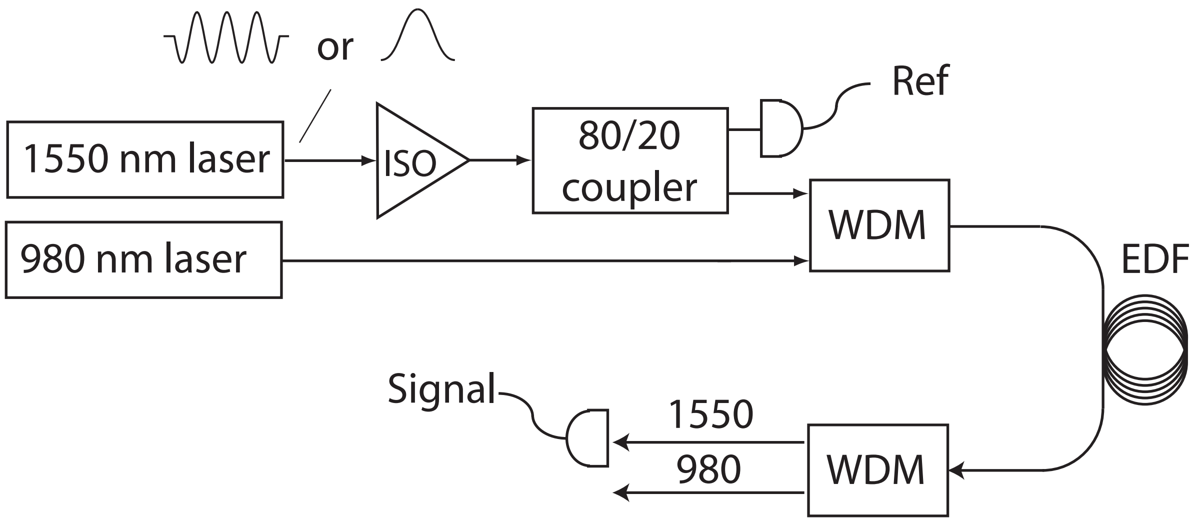




Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

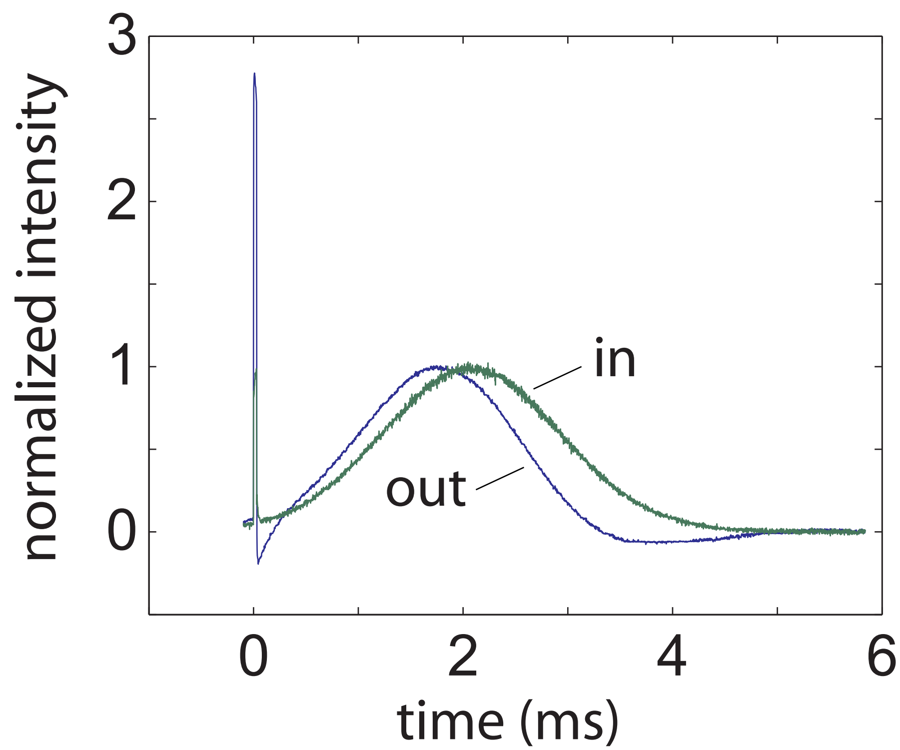
# Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier




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

Procedure

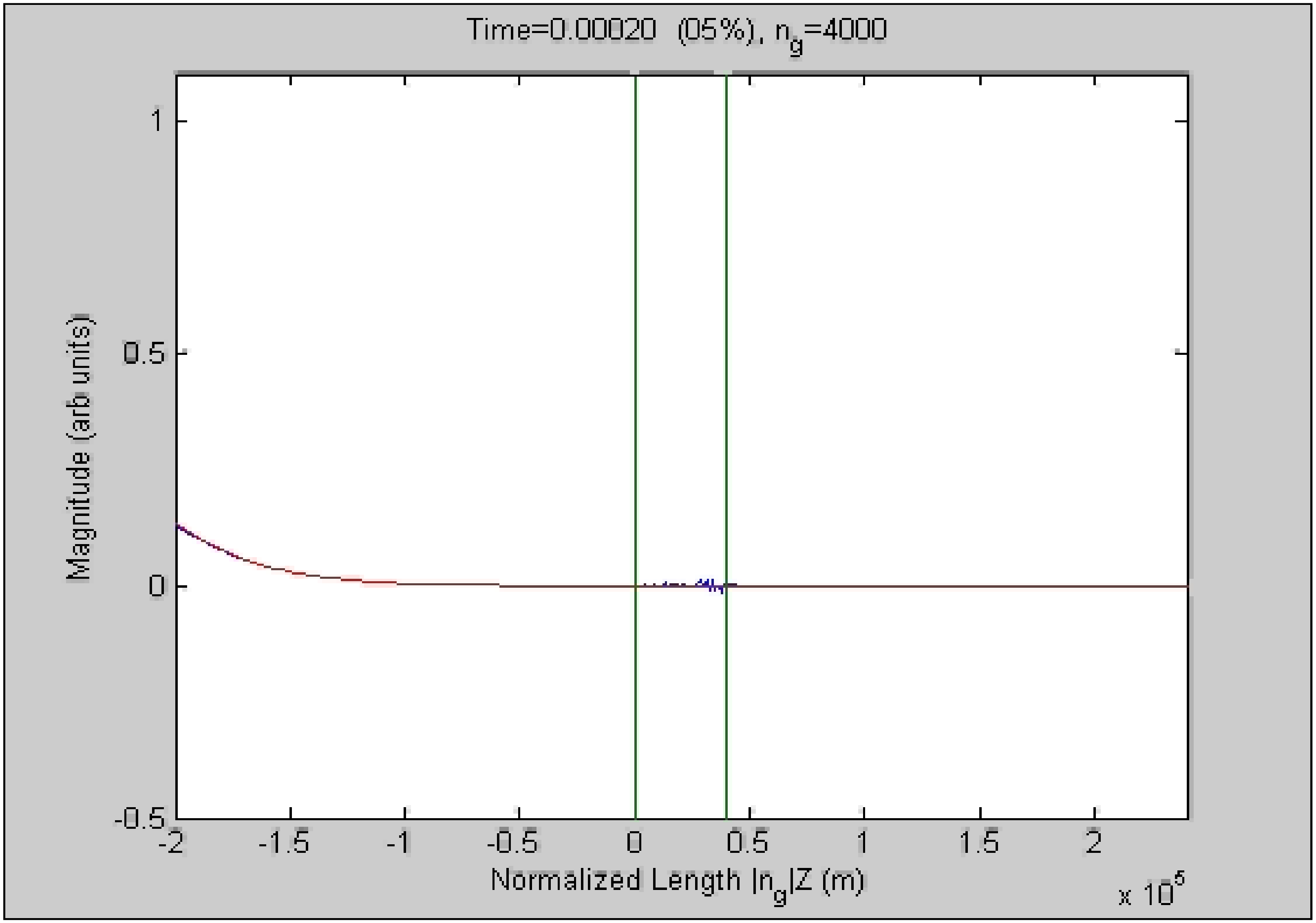
- cutback method
- couplers embedded in fiber




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

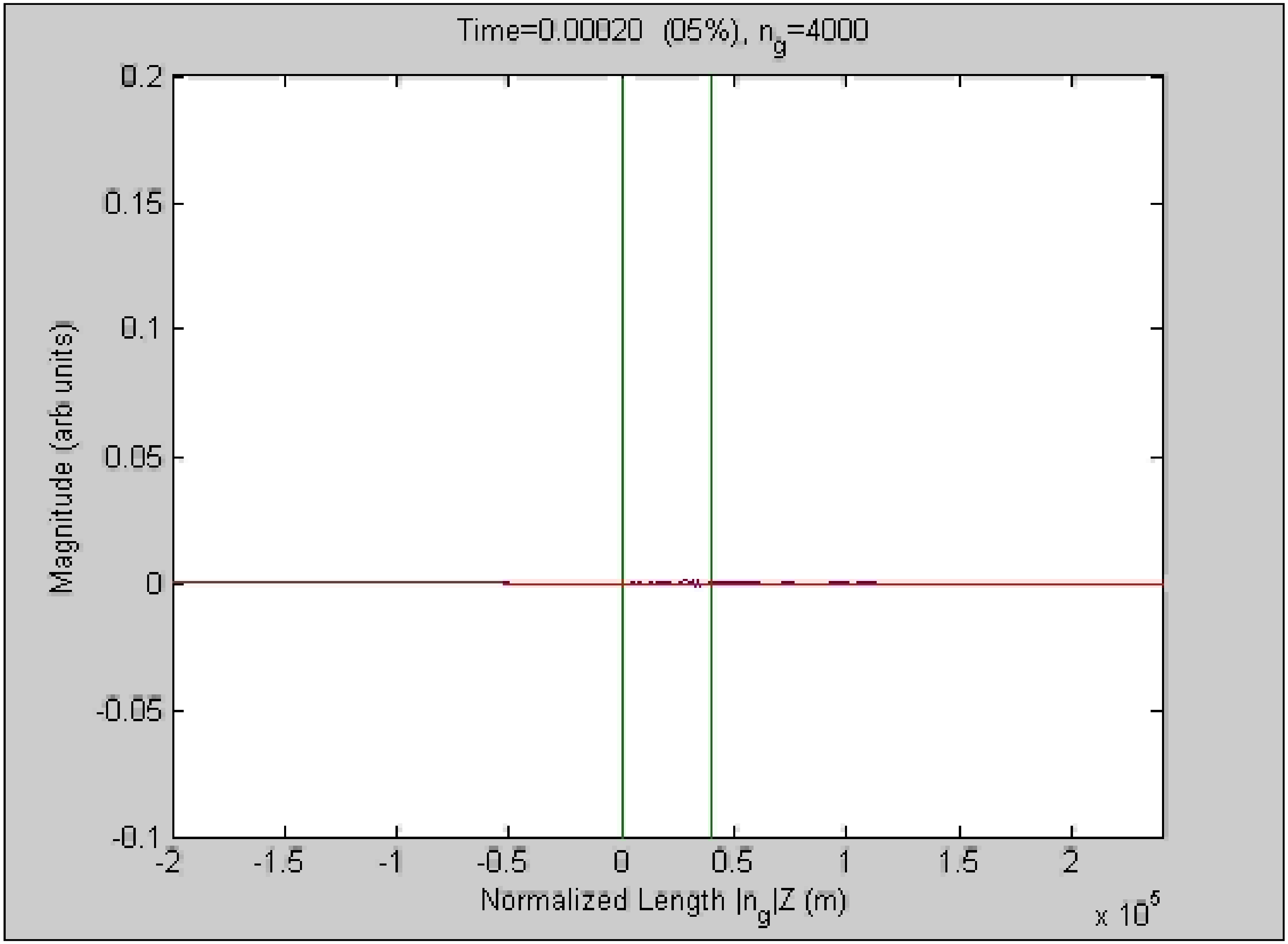
# Experimental Results: Backward Propagation in Erbium-Doped Fiber

## Normalized: (Amplification removed numerically)

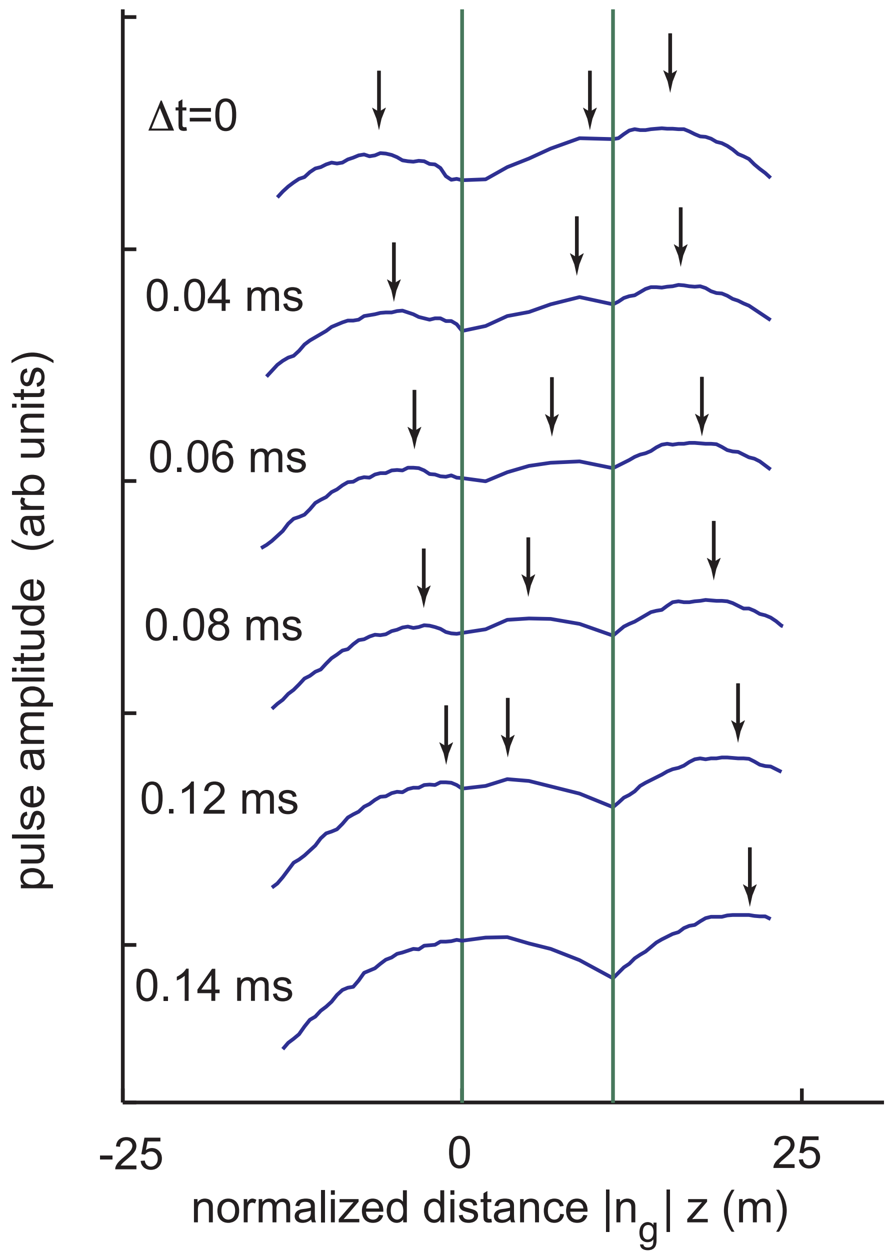


# Experimental Results: Backward Propagation in Erbium-Doped Fiber

## 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.

(Of course, many other workers have measured negative time delays. Our contribution was to measure the pulse evolution within the material medium.)

# 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?****

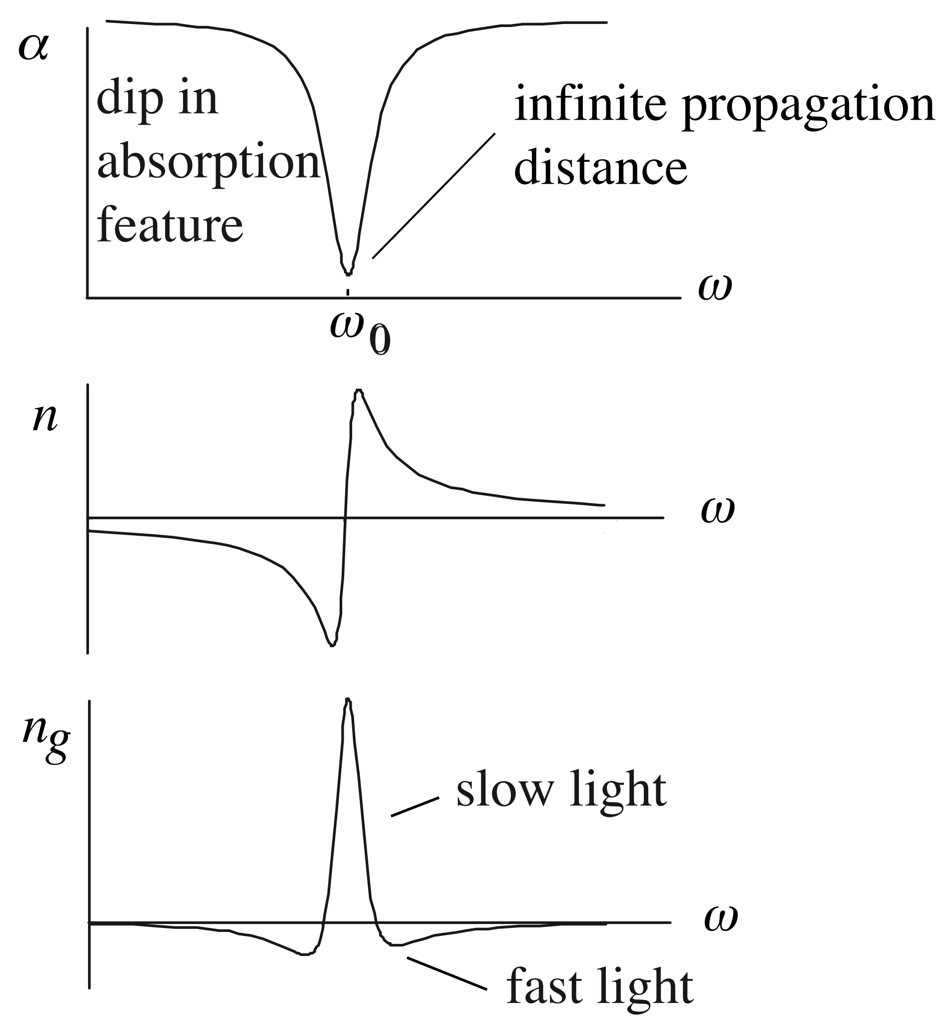
* Boyd, Gauthier, Gaeta, and Willner, PRA 2005

** 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.



# Why can one delay (but not advance) a pulse by an arbitrarily large amount?

Two crucial differences between slow and fast light

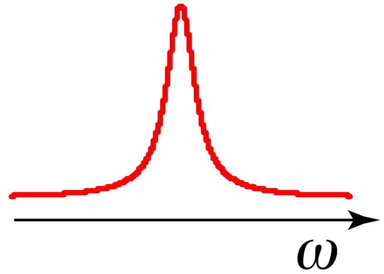
(1) First, note that we cannot use gains greater than approximately exp(16) at any frequency to avoid ASE. And we cannot have absorption larger than T = exp(-16) at the signal frequency, so signal can be measured. (Of course, the argument does not hinge on the value 16.) When examined quantitatively, these constraints impose a limit of at most two pulse-widths of delay or advancement.

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.

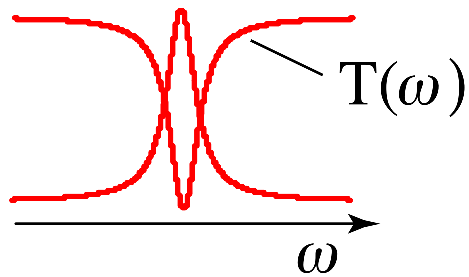
(2) Spectral reshaping of the pulse is the dominant competing effect in most slow/fast light systems. This also behaves differently for slow and fast-light systems, as we shall now see.

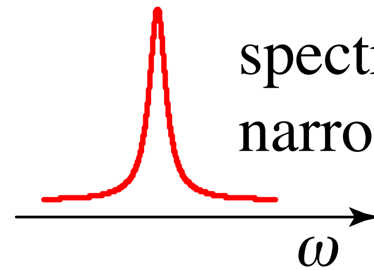
# Influence of Spectral Reshaping
## (Line-Center Operation, Dip in Gain or Absorption Feature)

input pulse



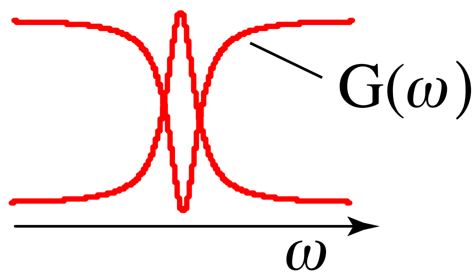

output pulse
slow-light

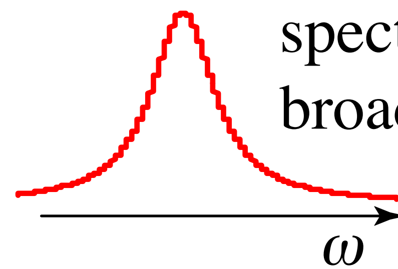



spectrally
narrowed pulse

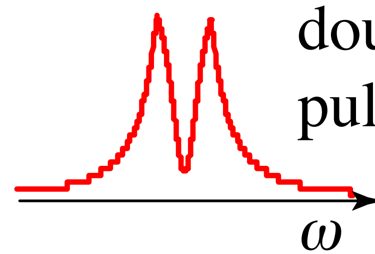
output pulse
fast-light




spectrally
broadened pulse

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




double-humped
pulse

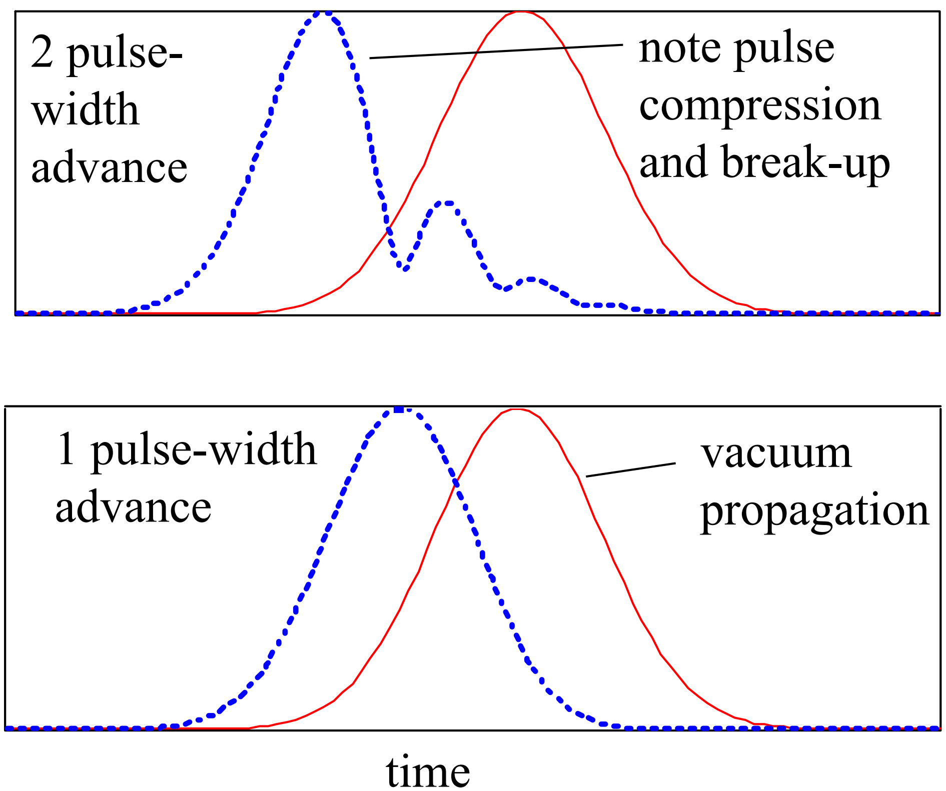
# Numerical Results: Propagation through a Linear Dispersive Medium

Fast light: single Lorentzian absorption line
- T = exp(-16)
- vary absorption line width to control advance

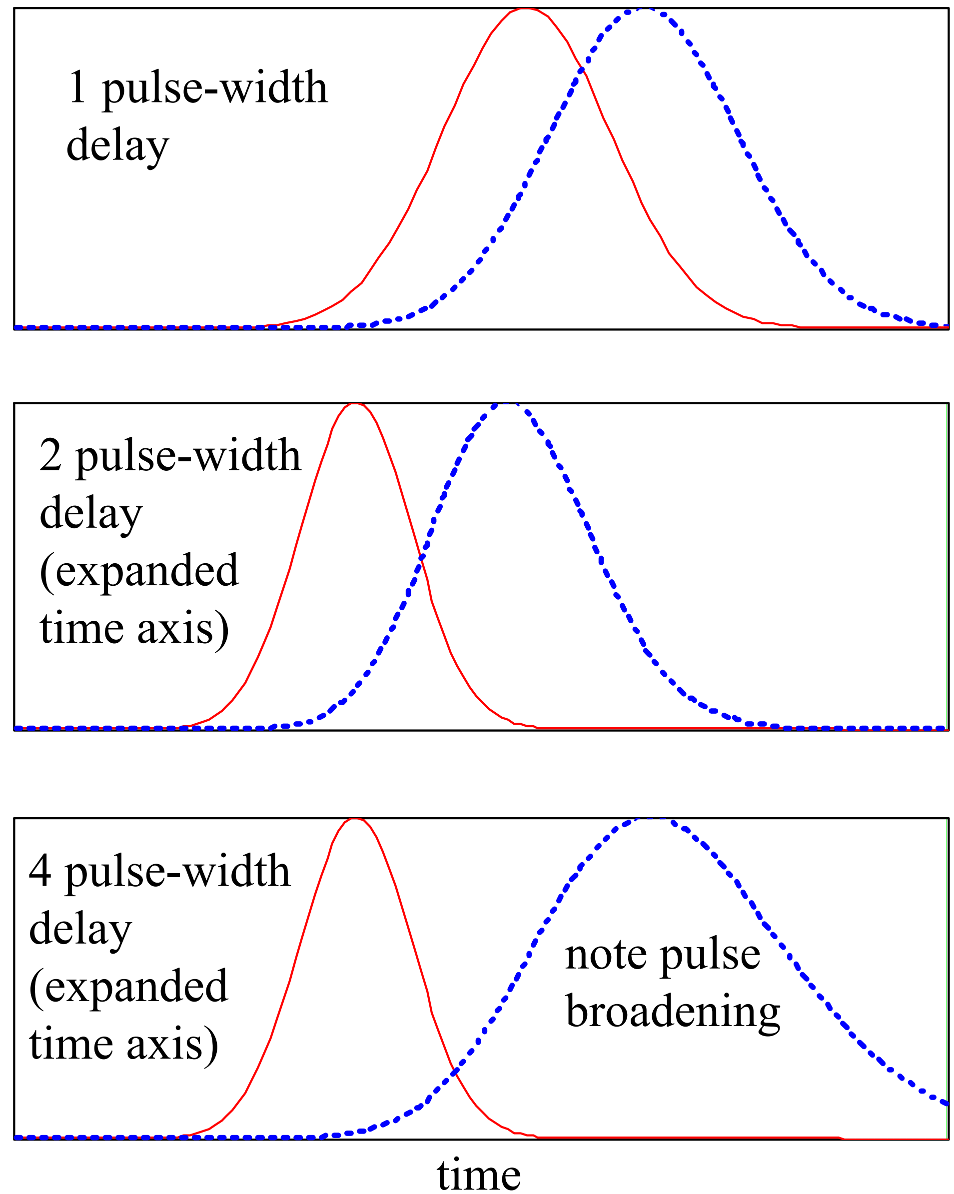
Slow light: single Lorentzian gain line
- T = exp(+16)
- vary absorption line width to control delay

Same Gaussian input pulse in all cases

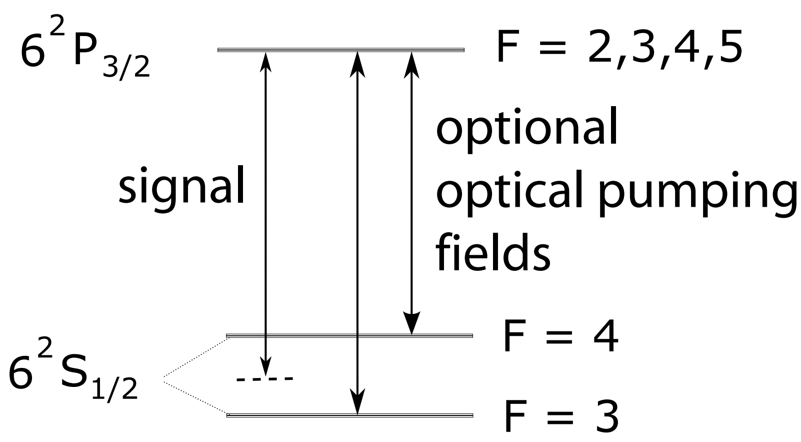
## Fast Light Results

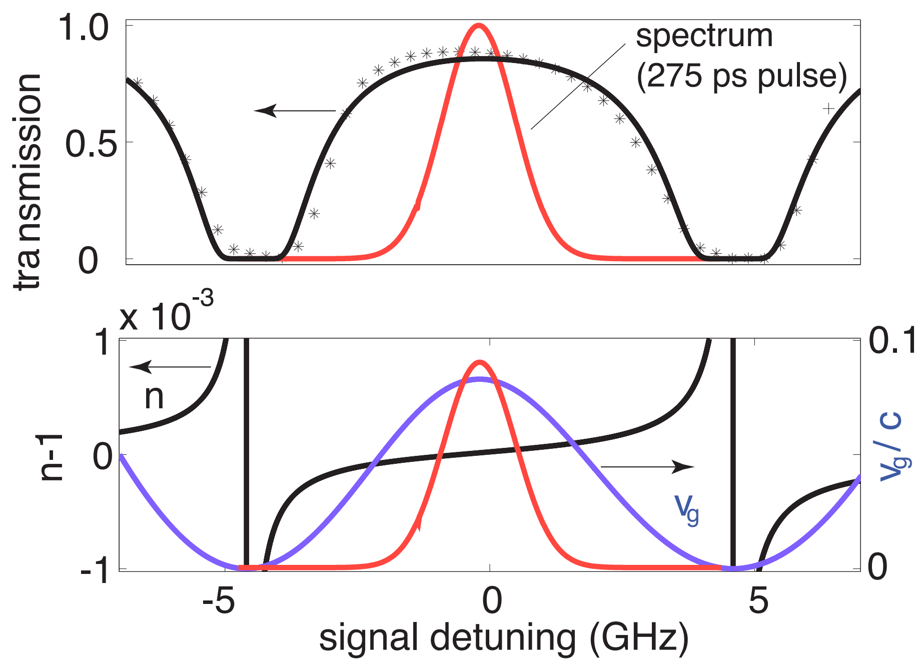



## Slow Light Results

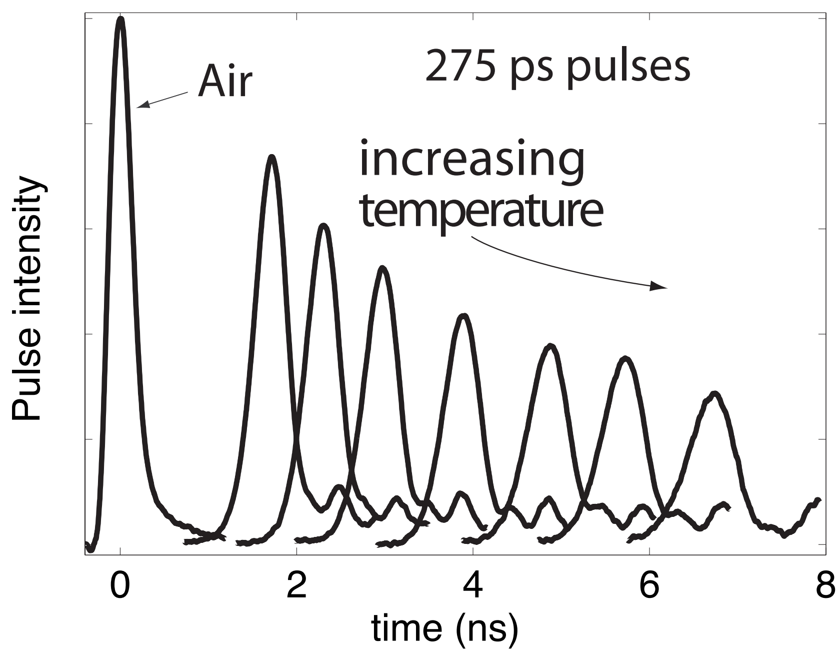


# Tunable Delays of up to 80 Pulse Widths in Atomic Cesium Vapor

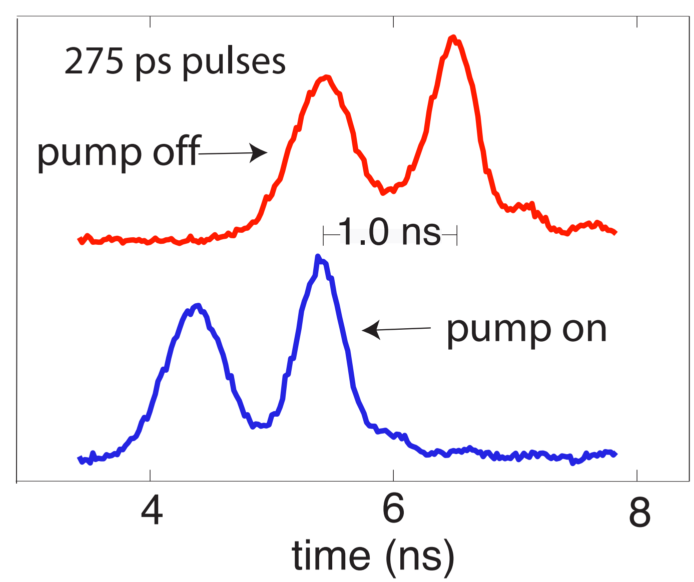



• coarse tuning: temperature




• fine tuning: optical pumping



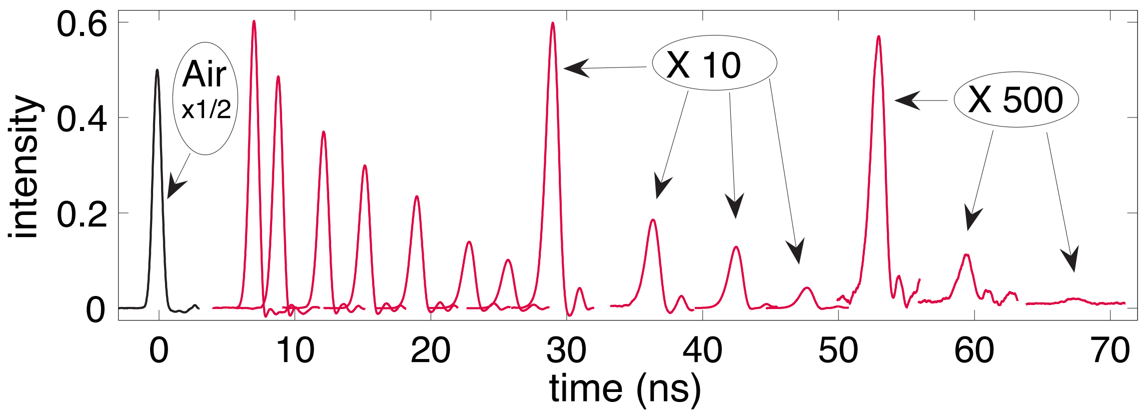

Camacho, Peck, Howell, Schweinsberg, Boyd

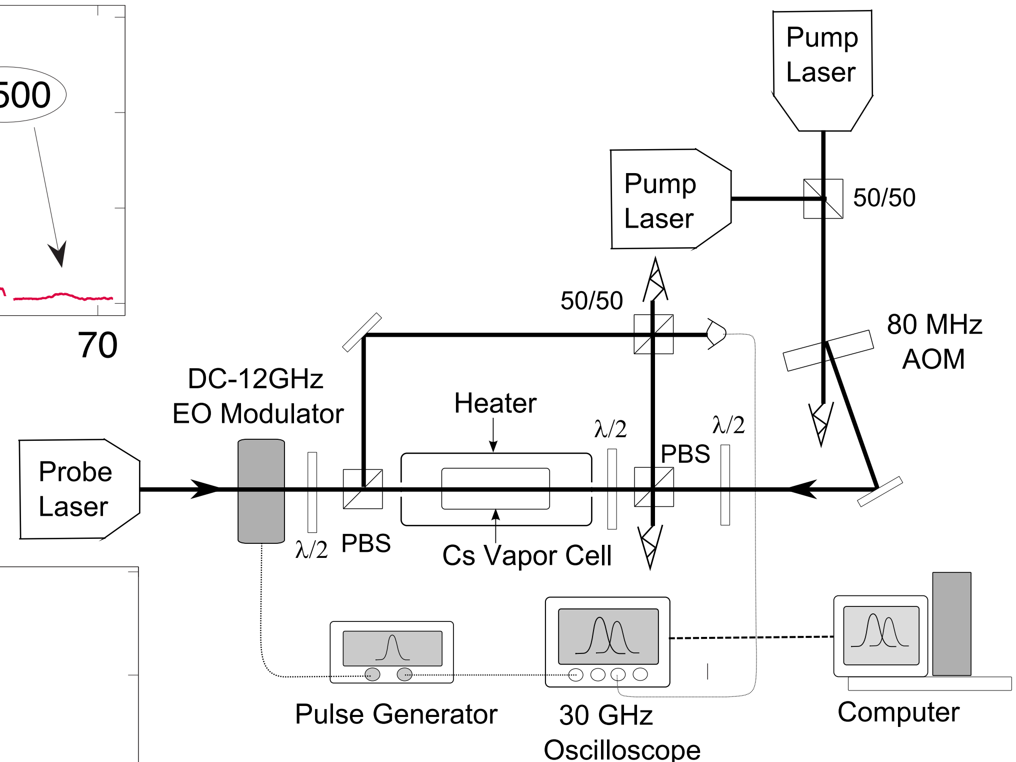
# Tunable Delays of up to 80 Pulse Widths in Atomic Cesium Vapor

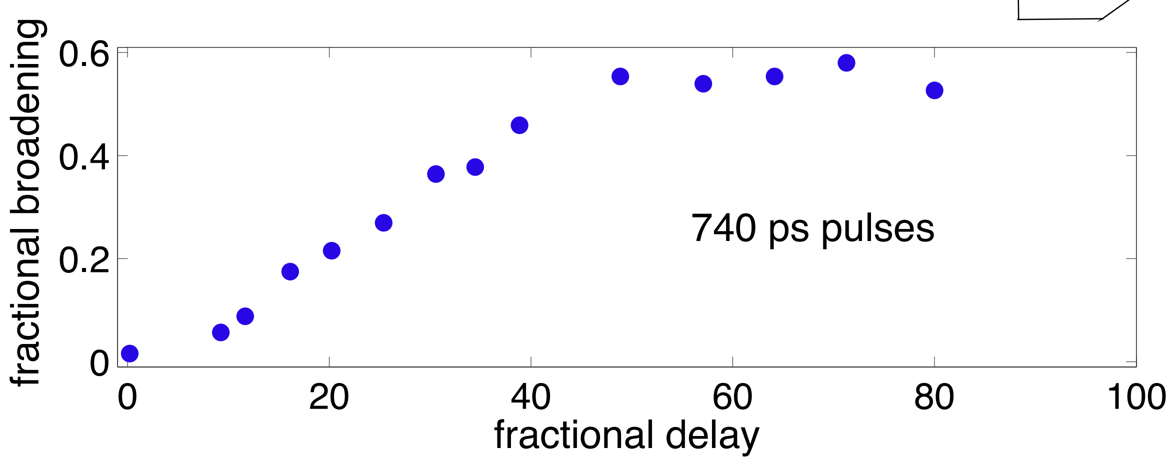
Comment: In EIT based slow light, spectral reshaping is the dominant limitation. But far off resonance, this effect is negligible. Group velocity dispersion becomes important.

Longer input pulses lead to reduced gvd distortion and longer fractional delays

Results for 740 ps pulses




Camacho, Peck, Howell, Schweinsberg, Boyd

# How to Prevent Pulse Distortion (Which Can Limit Data Rates)

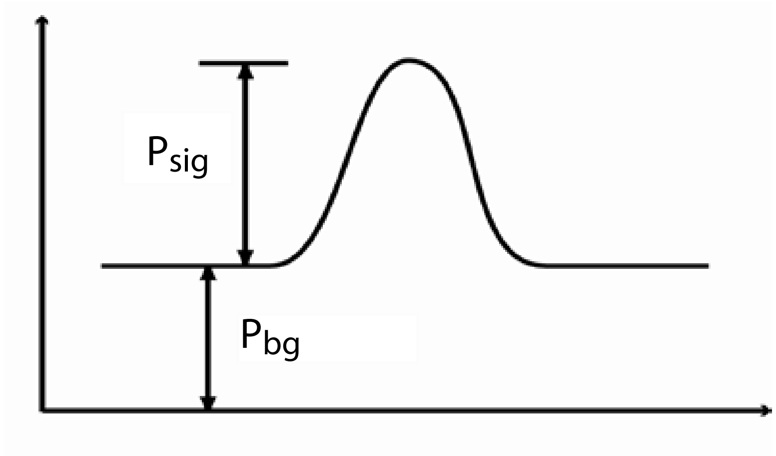
Two primary mechanisms for pulse distortion in EDFA

– Spectral broadening, leading to temporal compression
CPO gain dip causes spectral components in the wings to be amplified more than central components

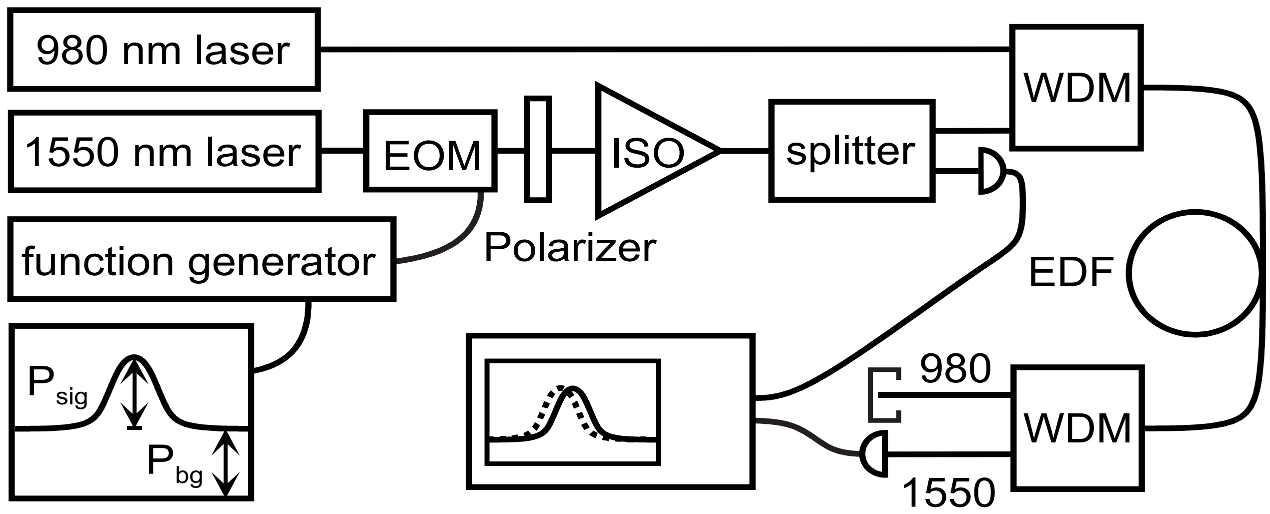
– Temporal gain recovery, leading to temporal broadening
Leading edge of signal pulse saturates gain, but for long pulses, the trailing edge can experience recovered gain

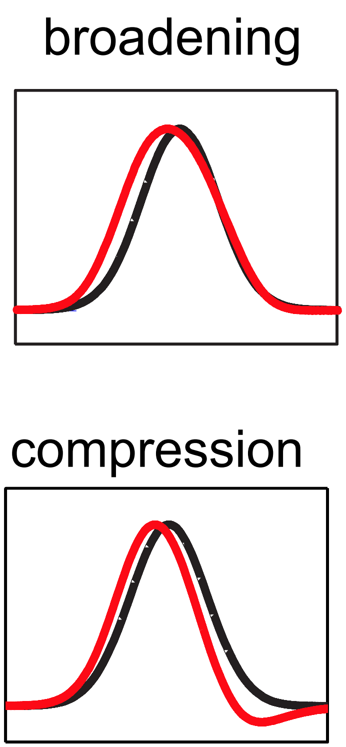
To minimize second effect, add a cw background to reduce the influence of gain recovery

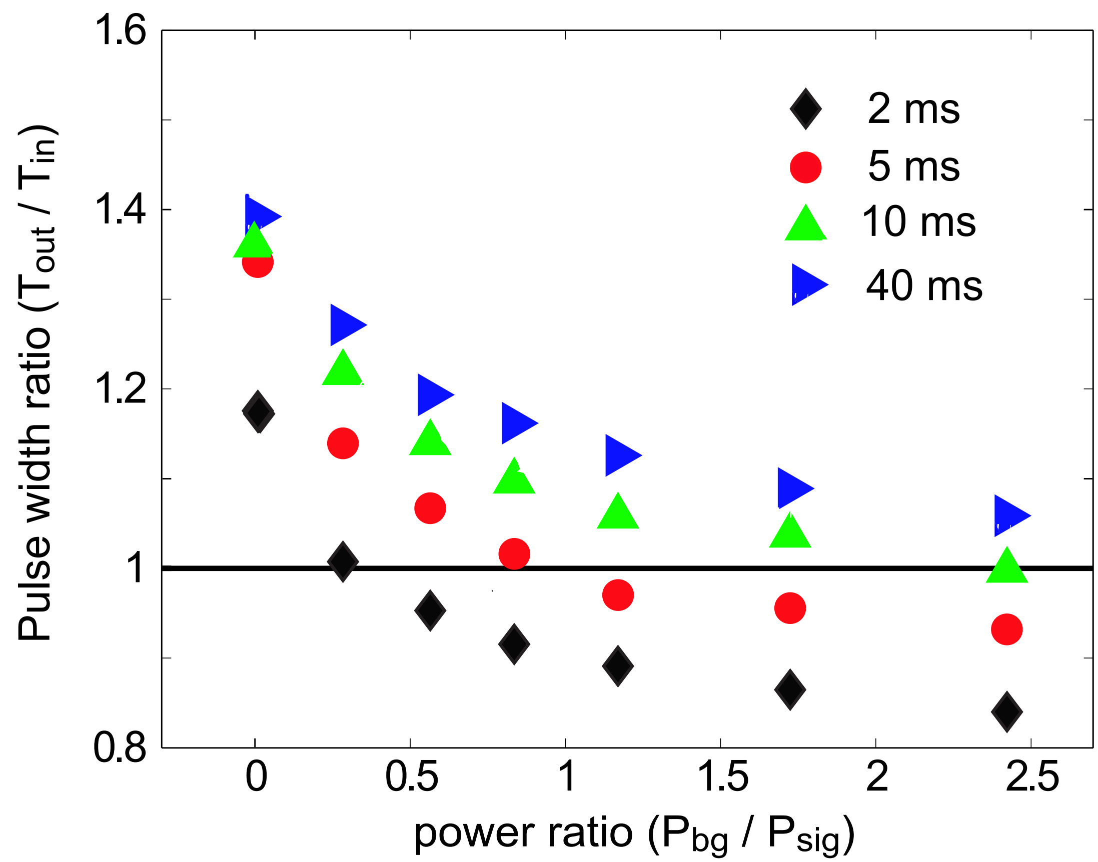
For the proper choice of background power, the two effects exactly cancel!



# Minimizing Pulse Distortion — Laboratory Results



# Summary

Slow-light techniques hold great promise for applications in telecommunications

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

Backwards and superluminal propagation are strongly counterintuitive, but are fully explained by standard physics.

# Special Thanks to My Students and Research Associates