Advances in Slow and Fast Light

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

Presented at PQE, Janauary 7, 2008.

Outlook: Advances in Slow and Fast Light

– Light can be made to go:

slow: $v << c$
fast: $v > c$
backwards: v negative
(here v is the group velocity.)

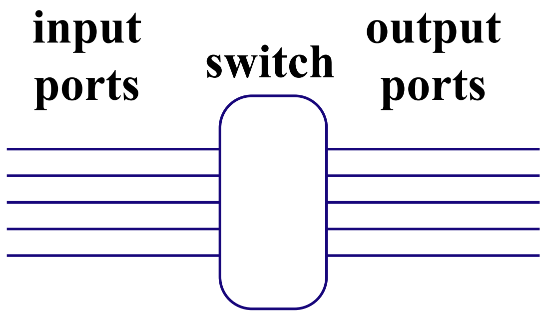
– Controllable light velocity leads to many applications

buffers for optical telecommunications
true time delay for microwave photonics

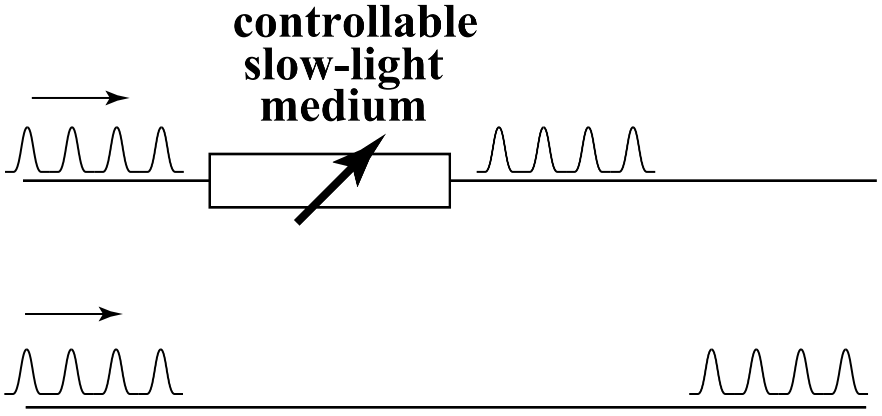
Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.

Slow Light and Optical Buffers

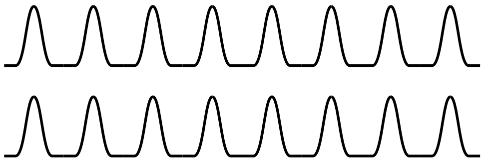
All-Optical Switch



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.

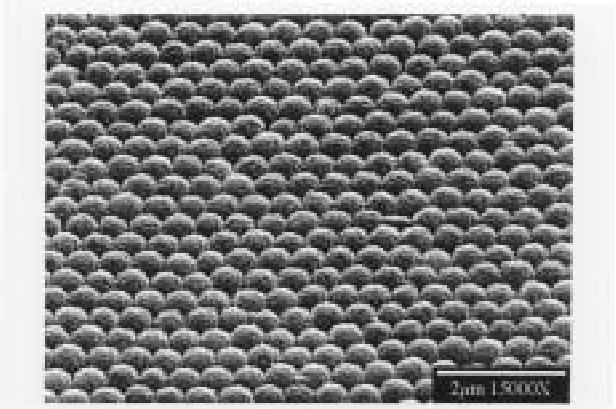
Daniel Blumenthal, UC Santa Barbara; Alexander Gaeta, Cornell University; Daniel Gauthier, Duke University; Alan Willner, University of Southern California; Robert Boyd, John Howell, University of Rochester

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

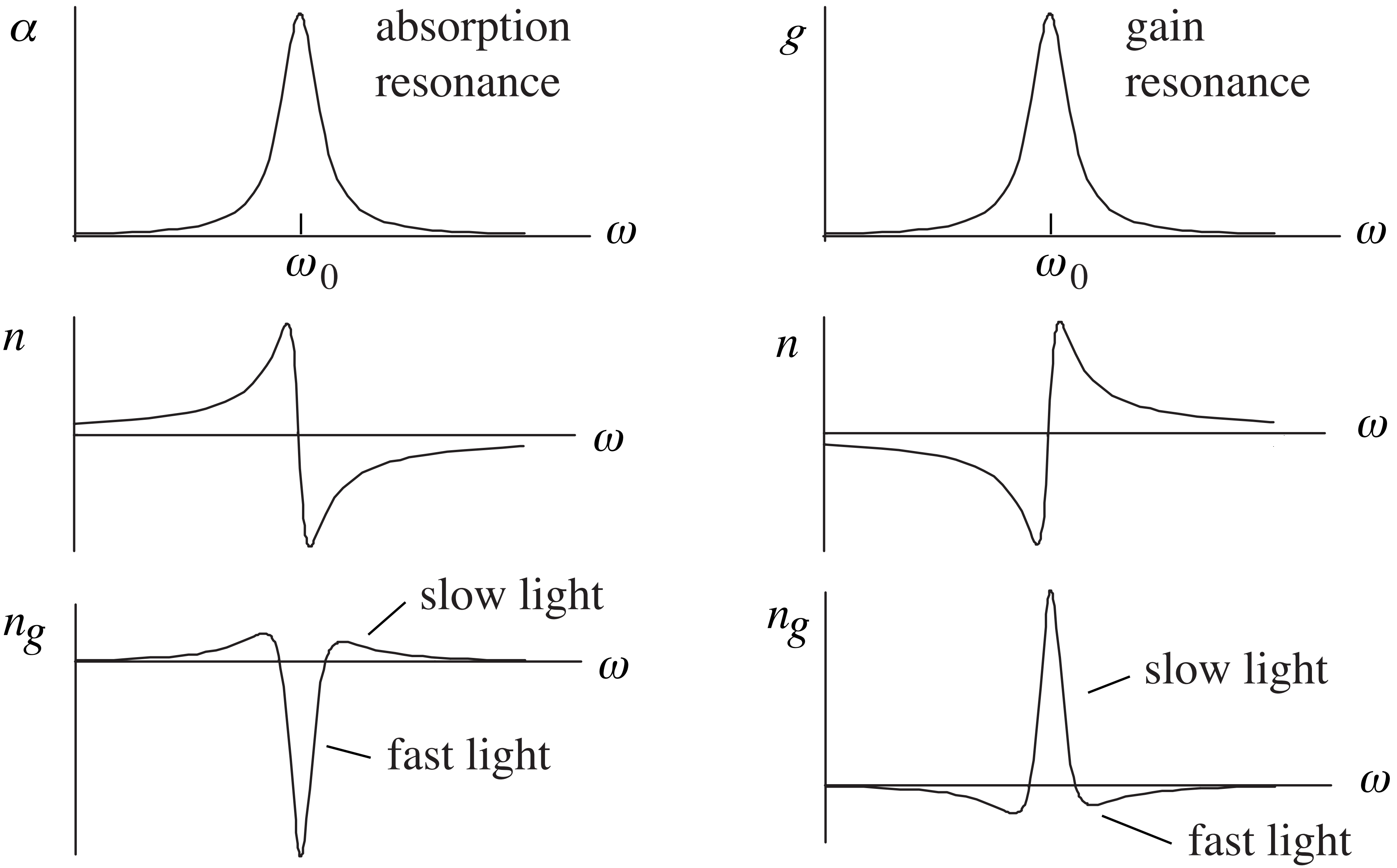
$$v_g = \frac{c}{n_g} \qquad\qquad n_g = n + \omega \frac{dn}{d\omega}$$

Want large dispersion to obtain extreme group velocities

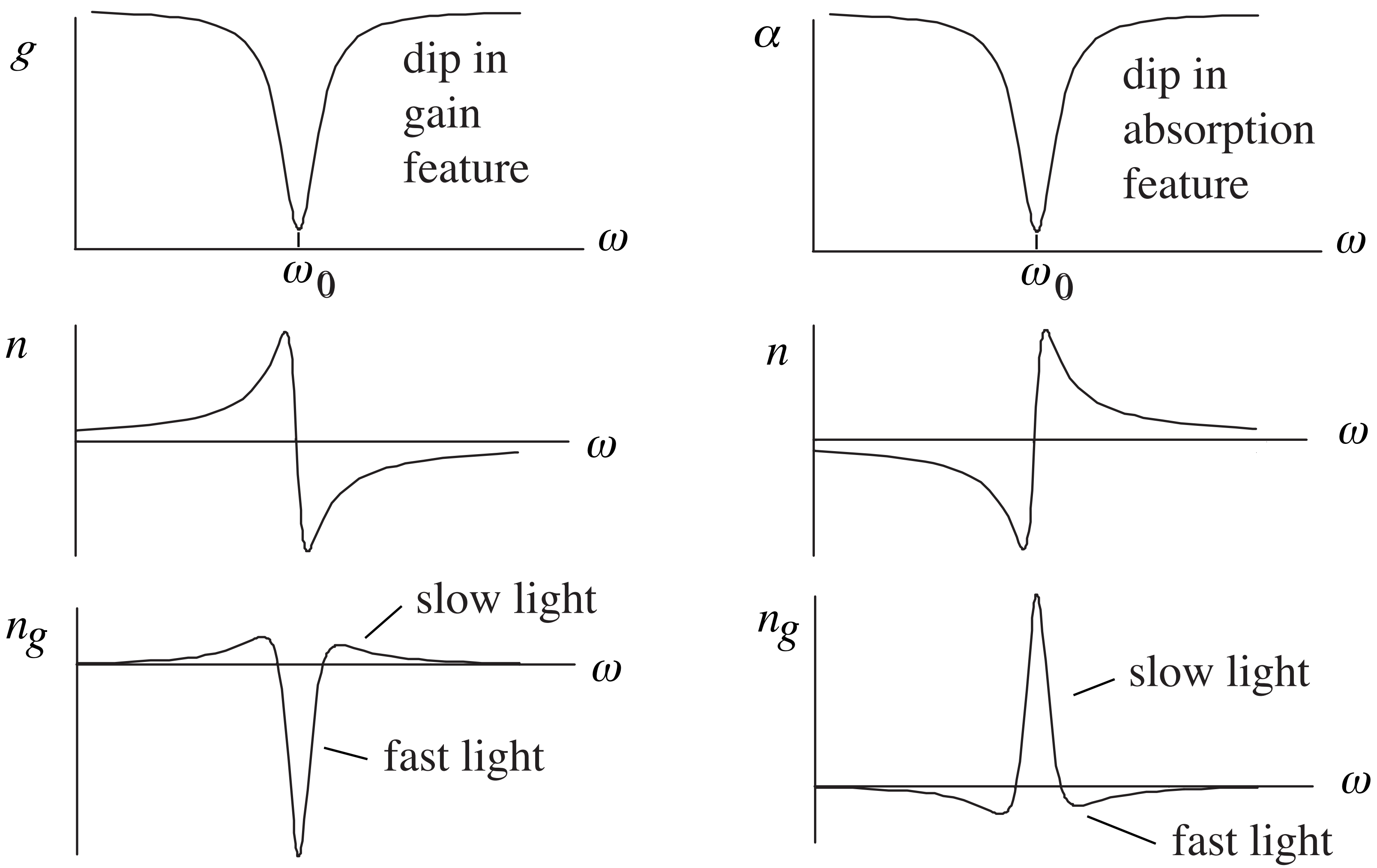
Sharp spectral features produce large dispersion.

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.

Light speed reduction to 17 metres per second in an ultracold atomic gas

Lene Vestergaard Hau*[2], S. E. Harris[3], Zachary Dutton*[2] & Cyrus H. Behroozi*§

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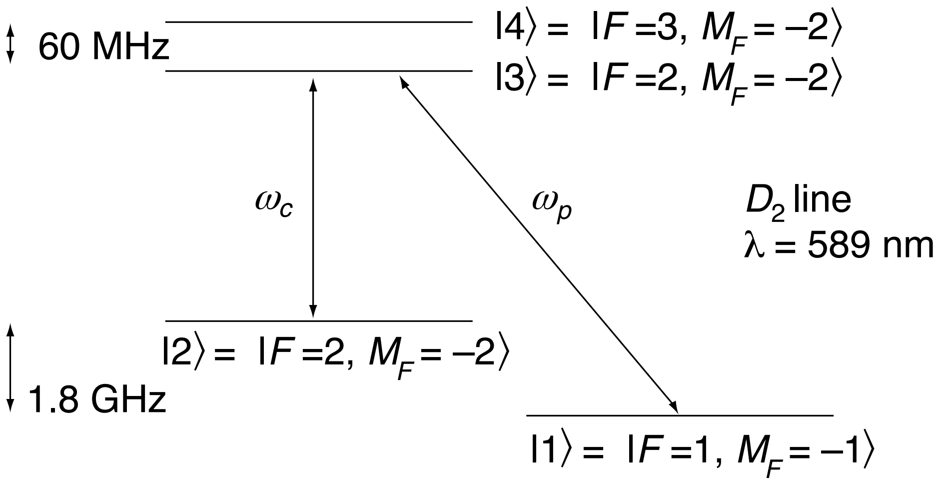
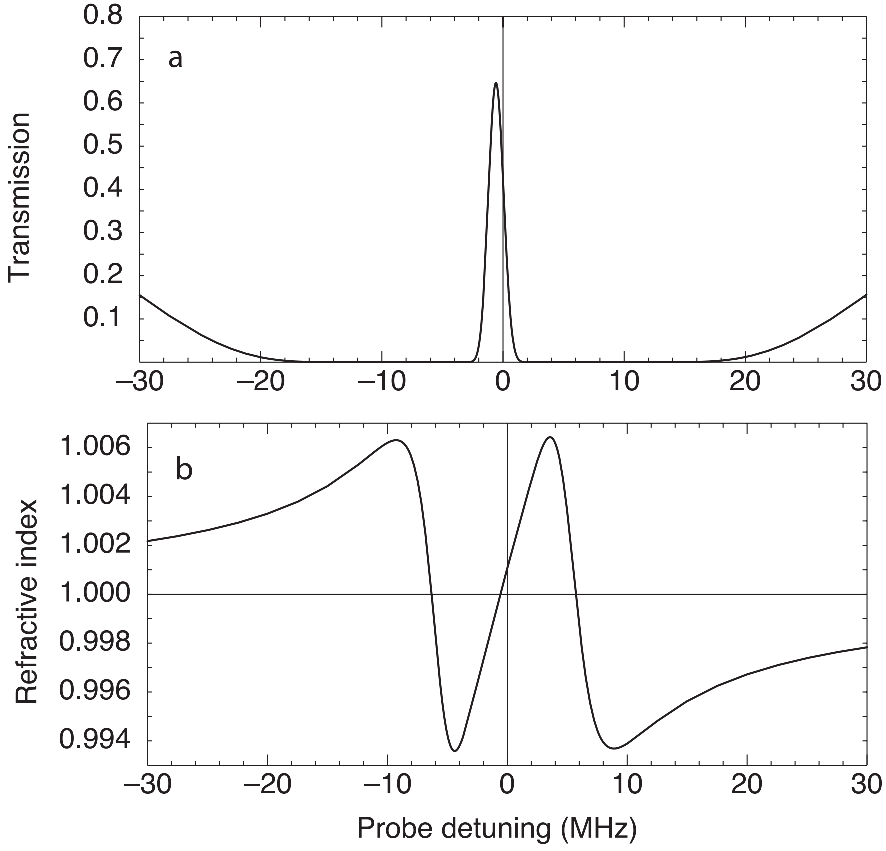
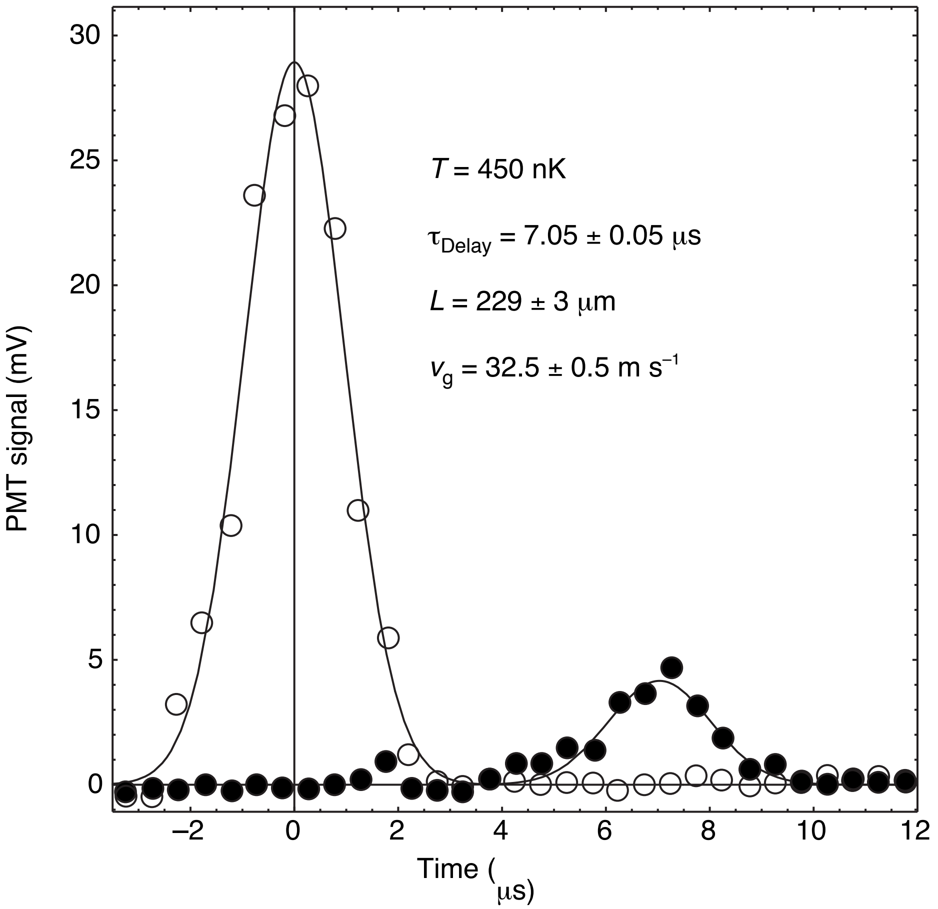
[2] Department of Physics, § Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
[3] Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA

NATURE | VOL 397 | 18 FEBRUARY 1999 |www.nature.com







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 in Ruby

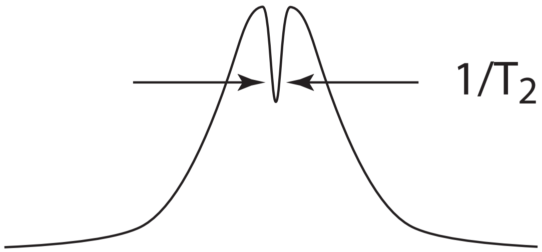
Recall that $n_g = n + \omega(dn/d\omega)$. Need a large $dn/d\omega$. (How?)

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

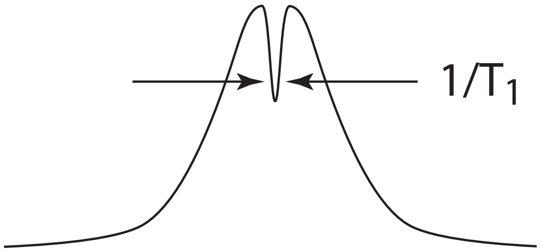
Well-known “trick” for doing so:

Make use of spectral holes due to population oscillations.

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



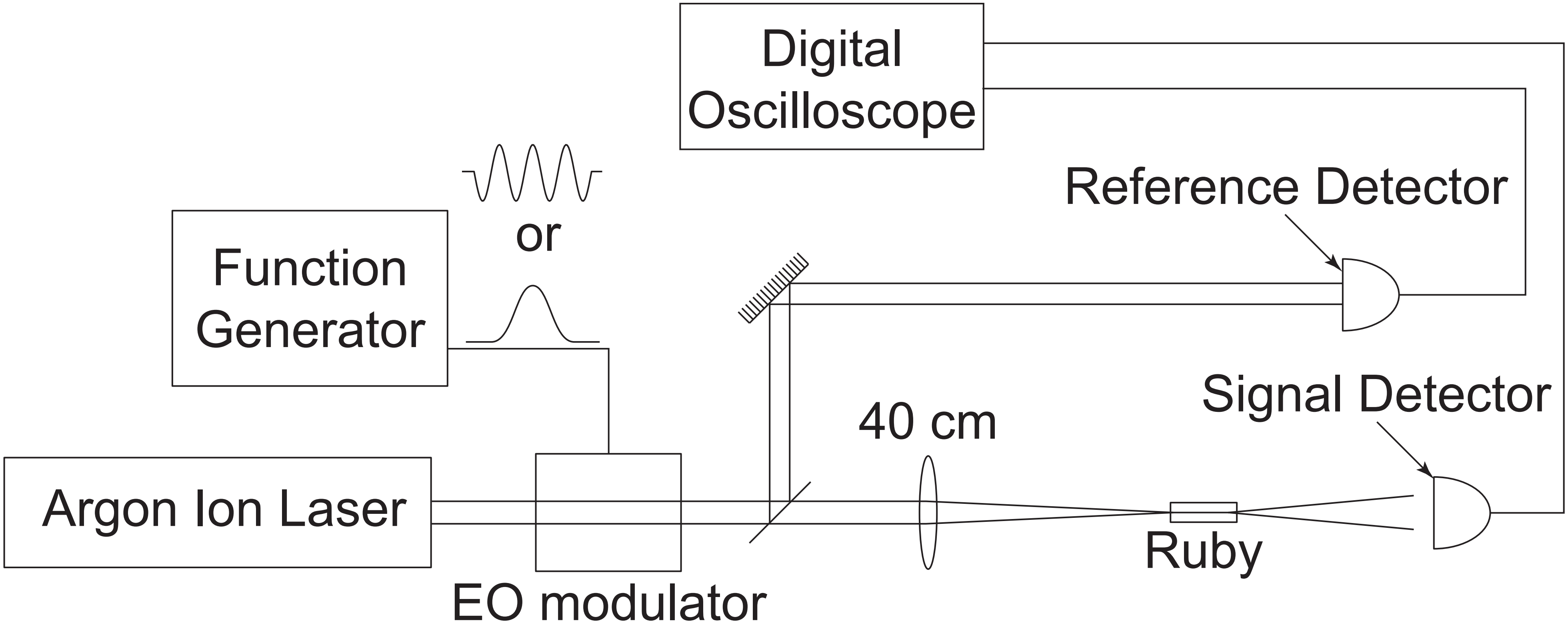
inhomogeneously
broadened medium



homogeneously
broadened medium
(or inhomogeneously
broadened)

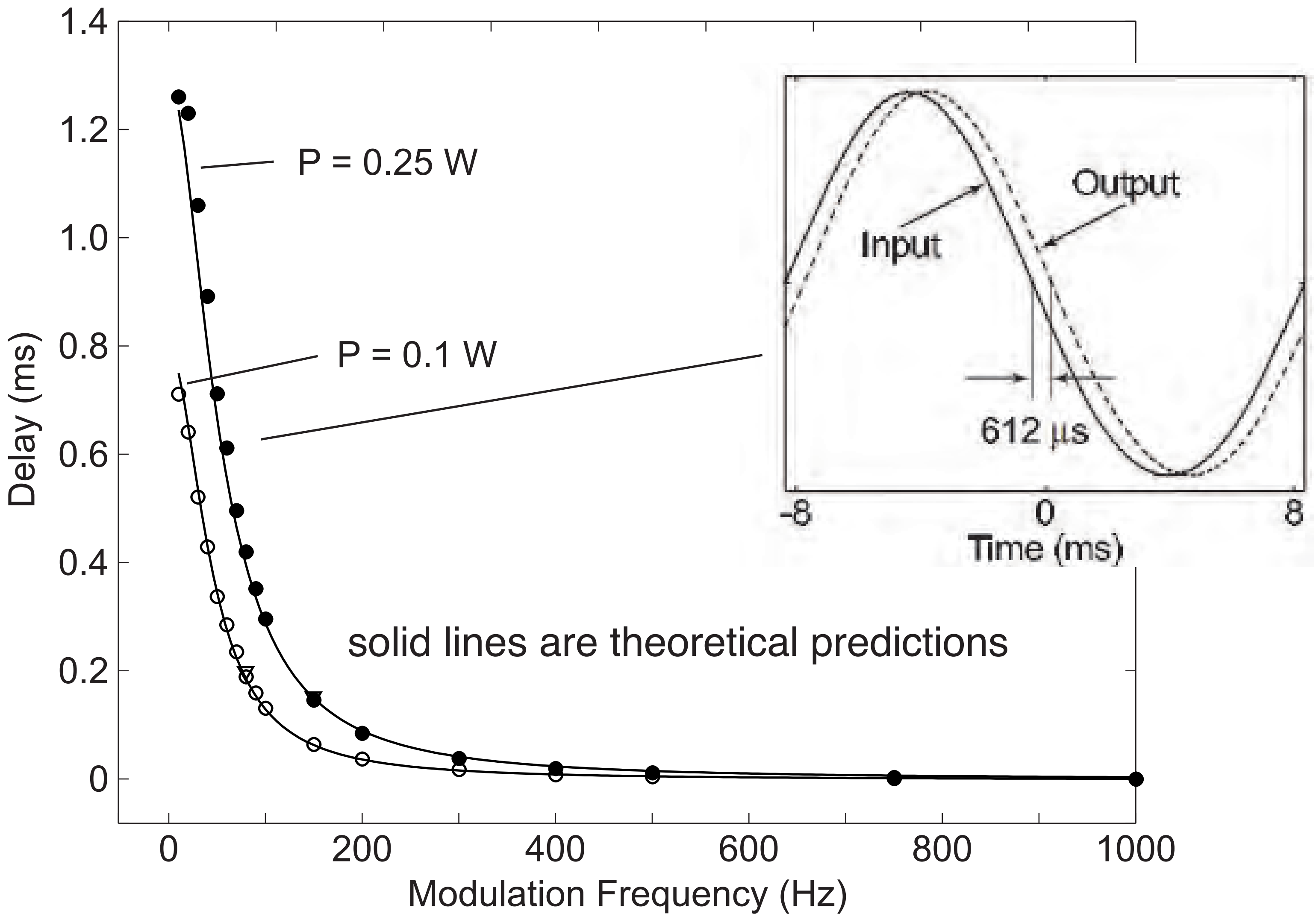
PRL 90,113903(2003).

Slow Light Experimental Setup



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

Measurement of Delay Time for Harmonic Modulation

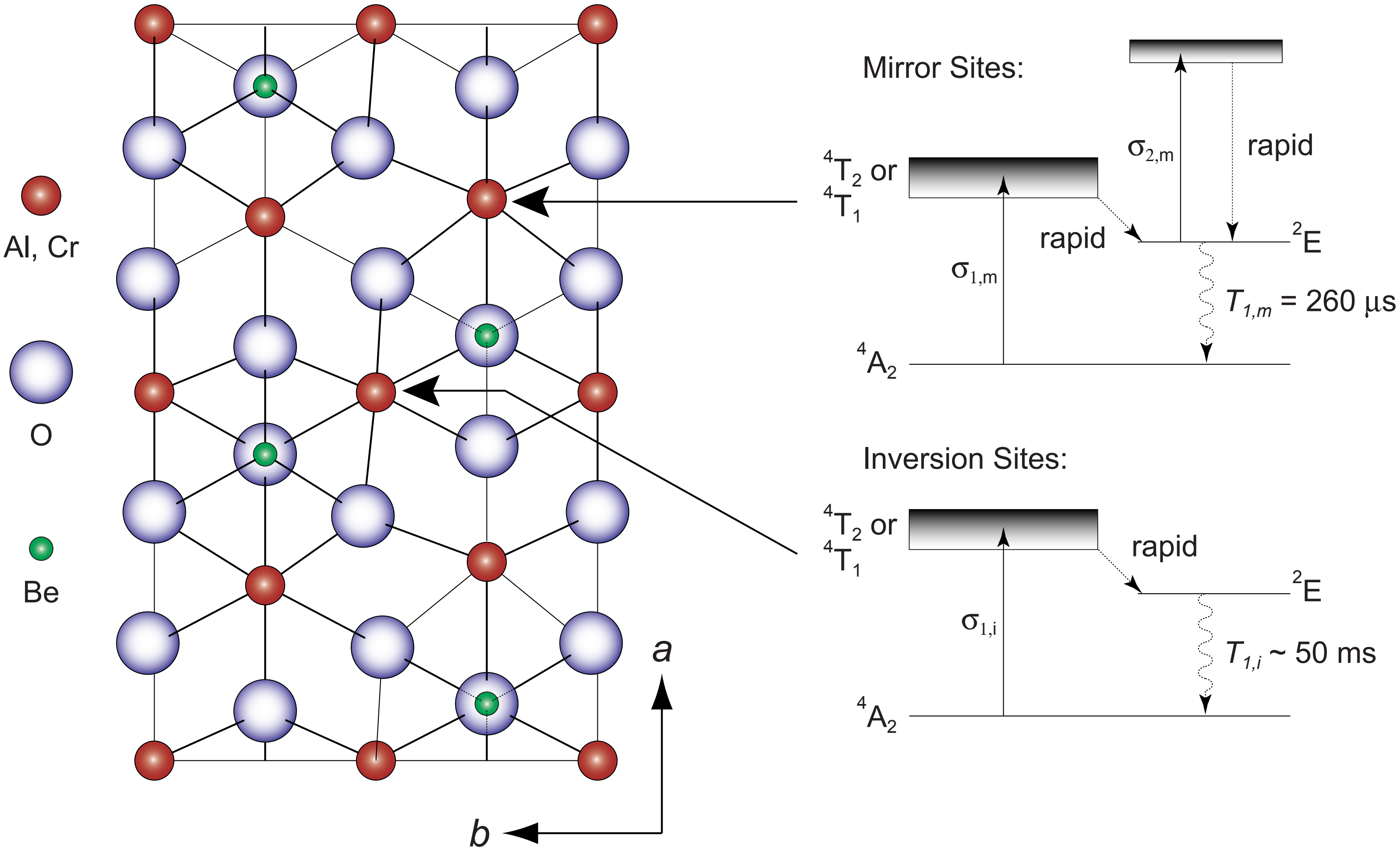


solid lines are theoretical predictions

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

Alexandrite Displays both Saturable and Reverse-Saturable Absorption

- Both slow and fast propagation observed in alexandrite

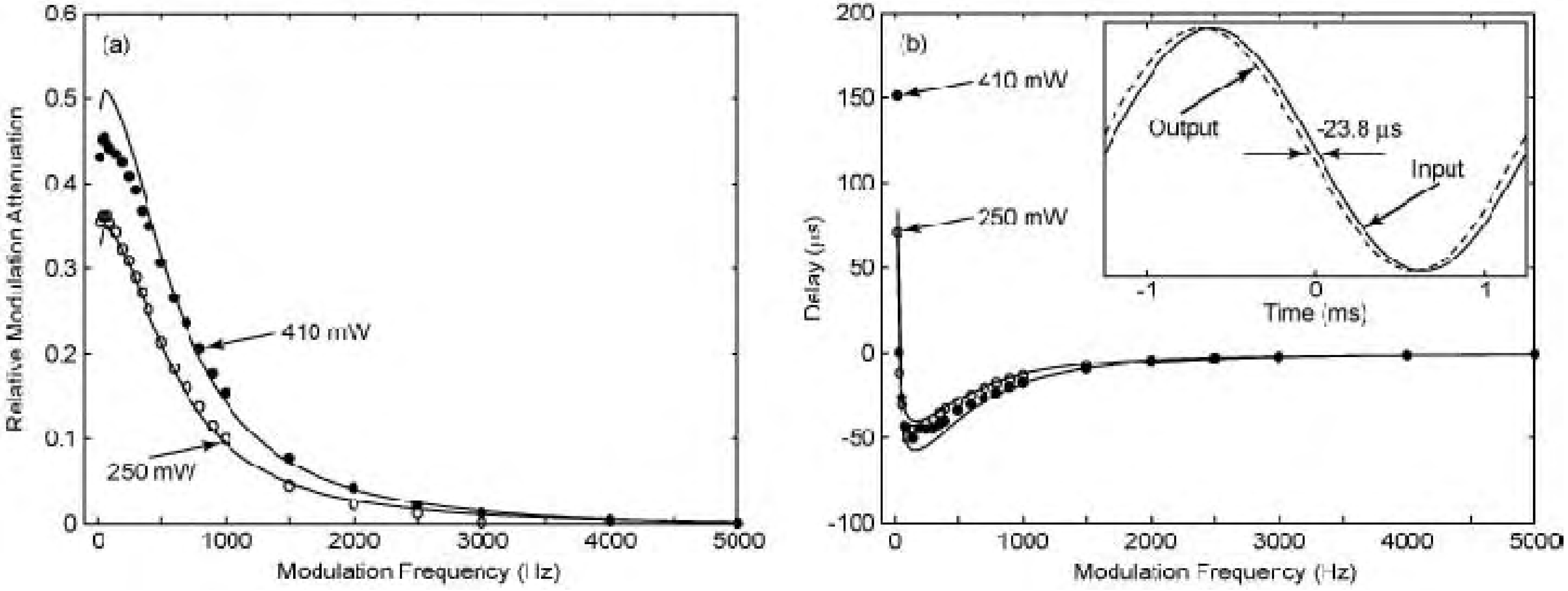


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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 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.

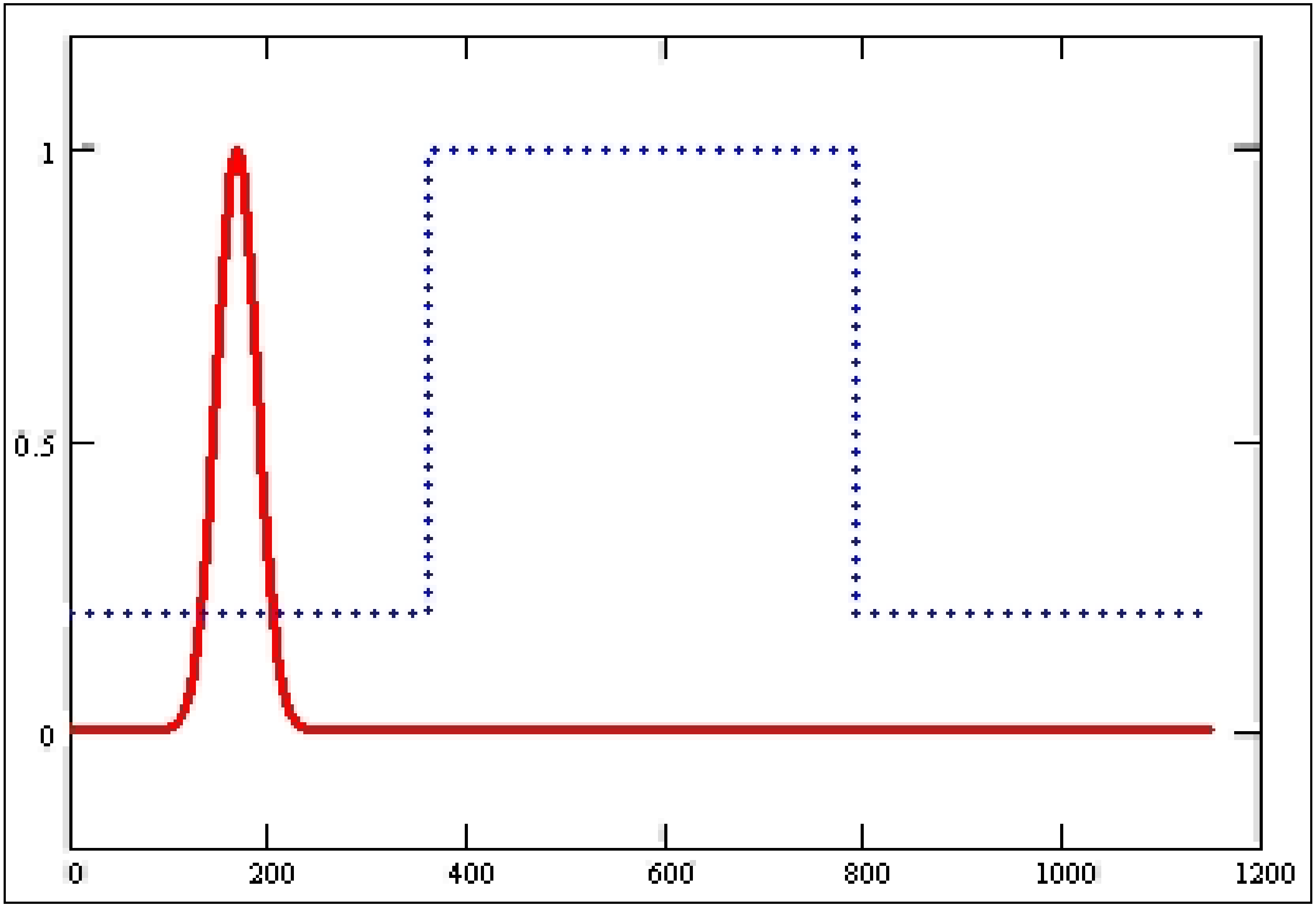
Study three cases:

Slow light $v_g = 0.5\ c$

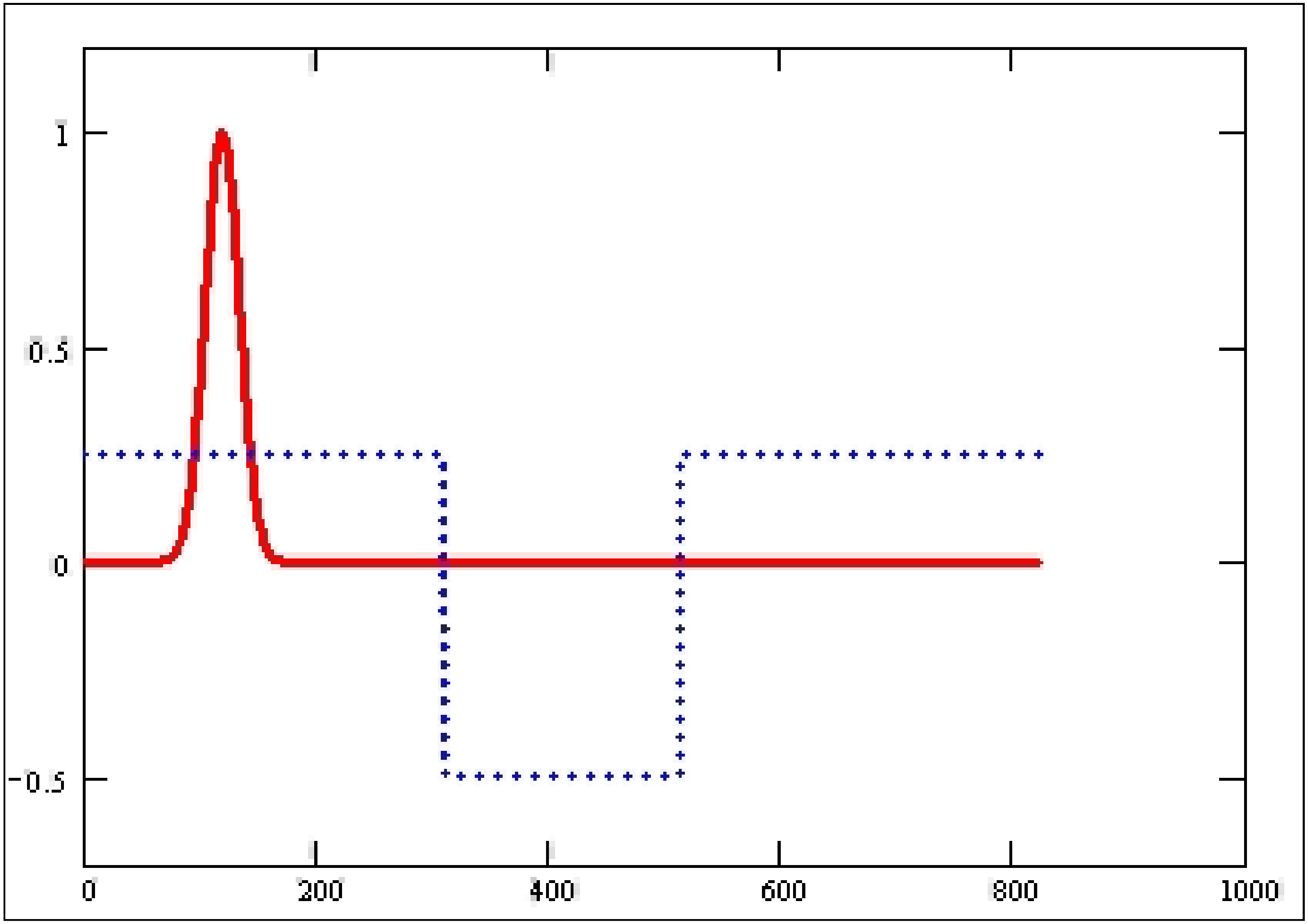
Fast light $v_g = 5\ c$ and $v_g = -2\ c$

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)

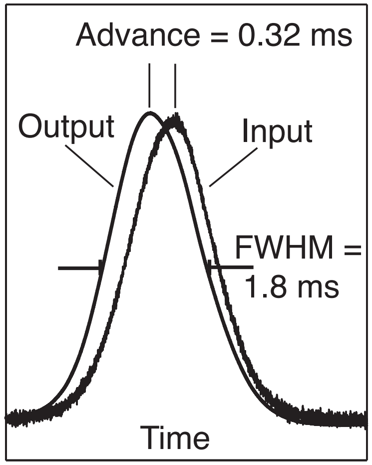


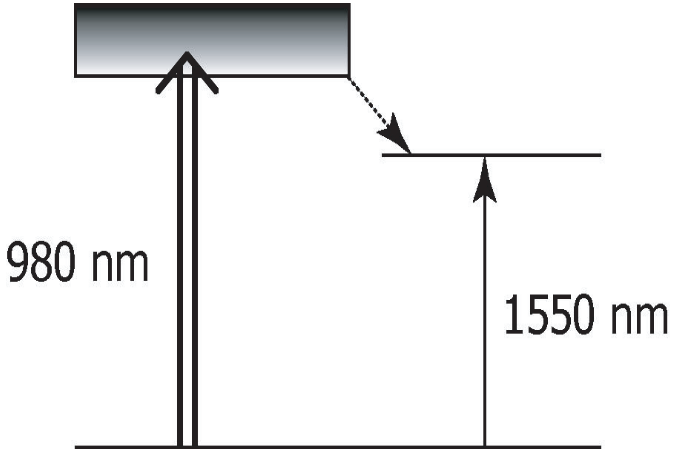
Pulse Propagation through a Backwards-Light Medium (n_g = -.5, v_g = -2 c)

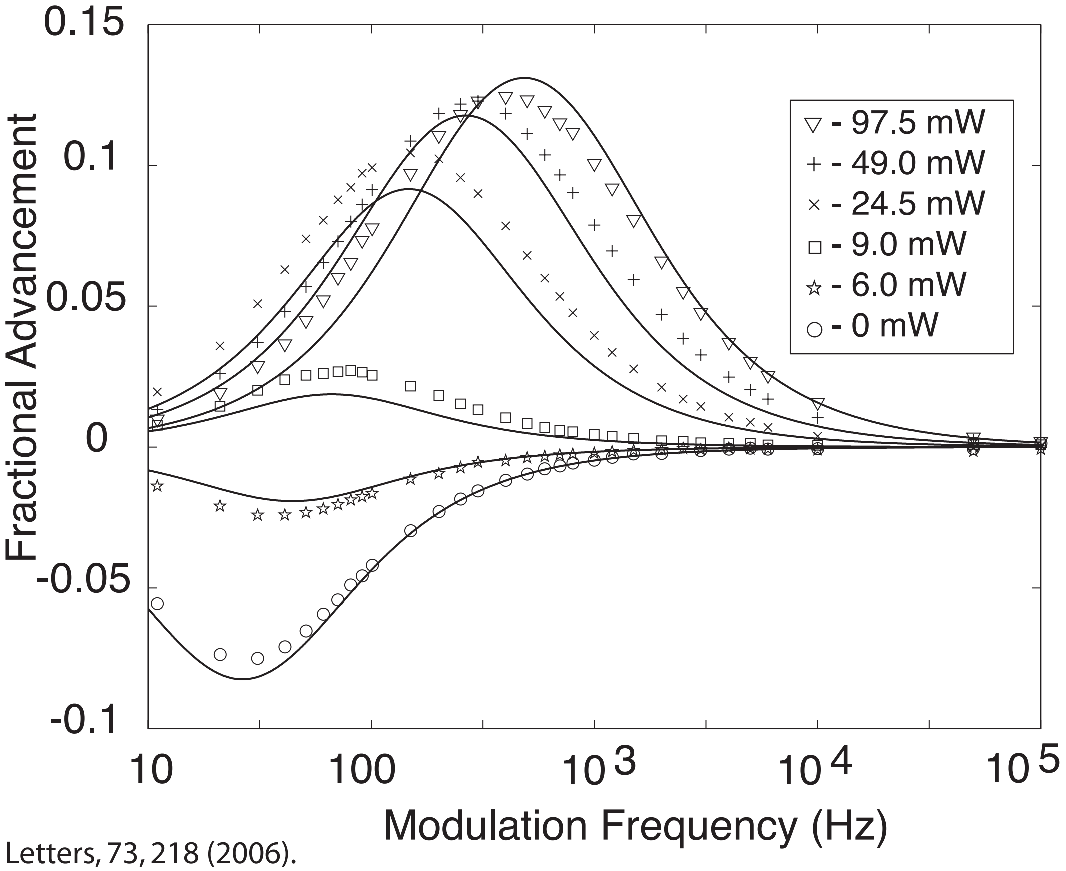


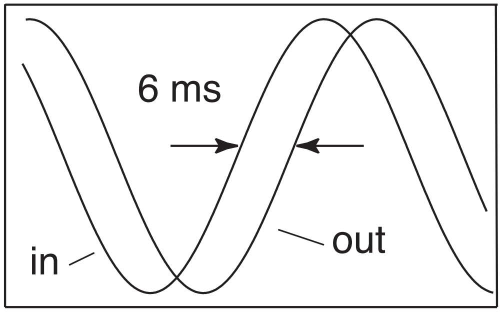
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



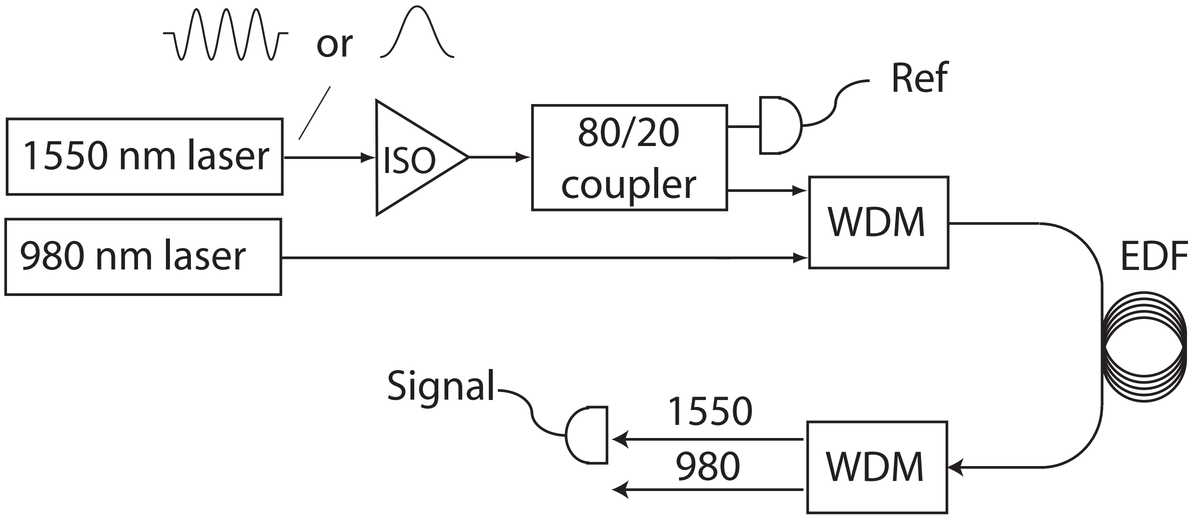






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo, Europhysics Letters, 73, 218 (2006).

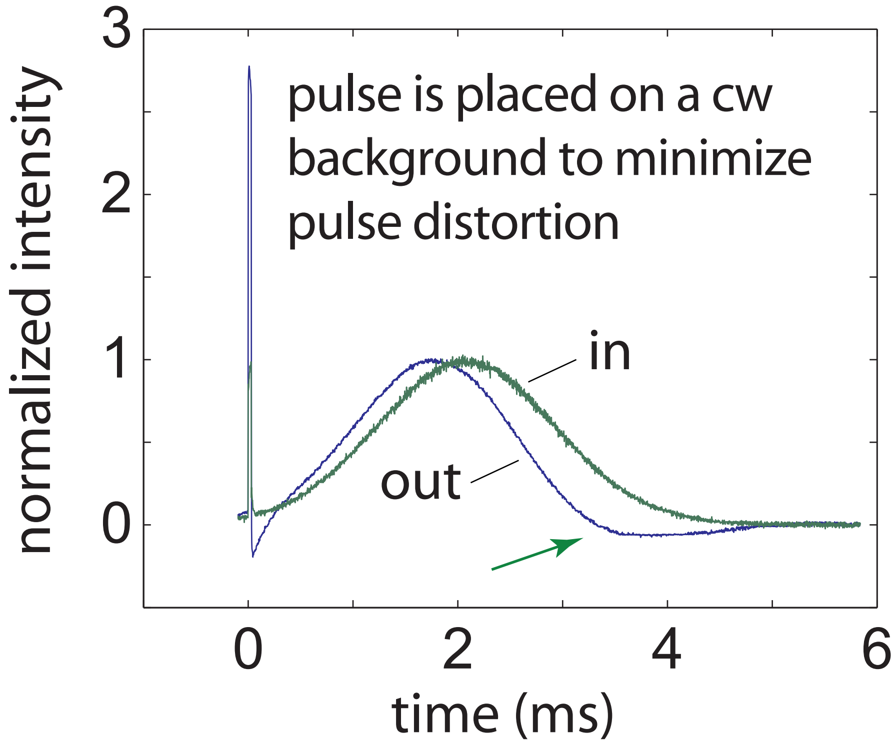
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



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

Procedure

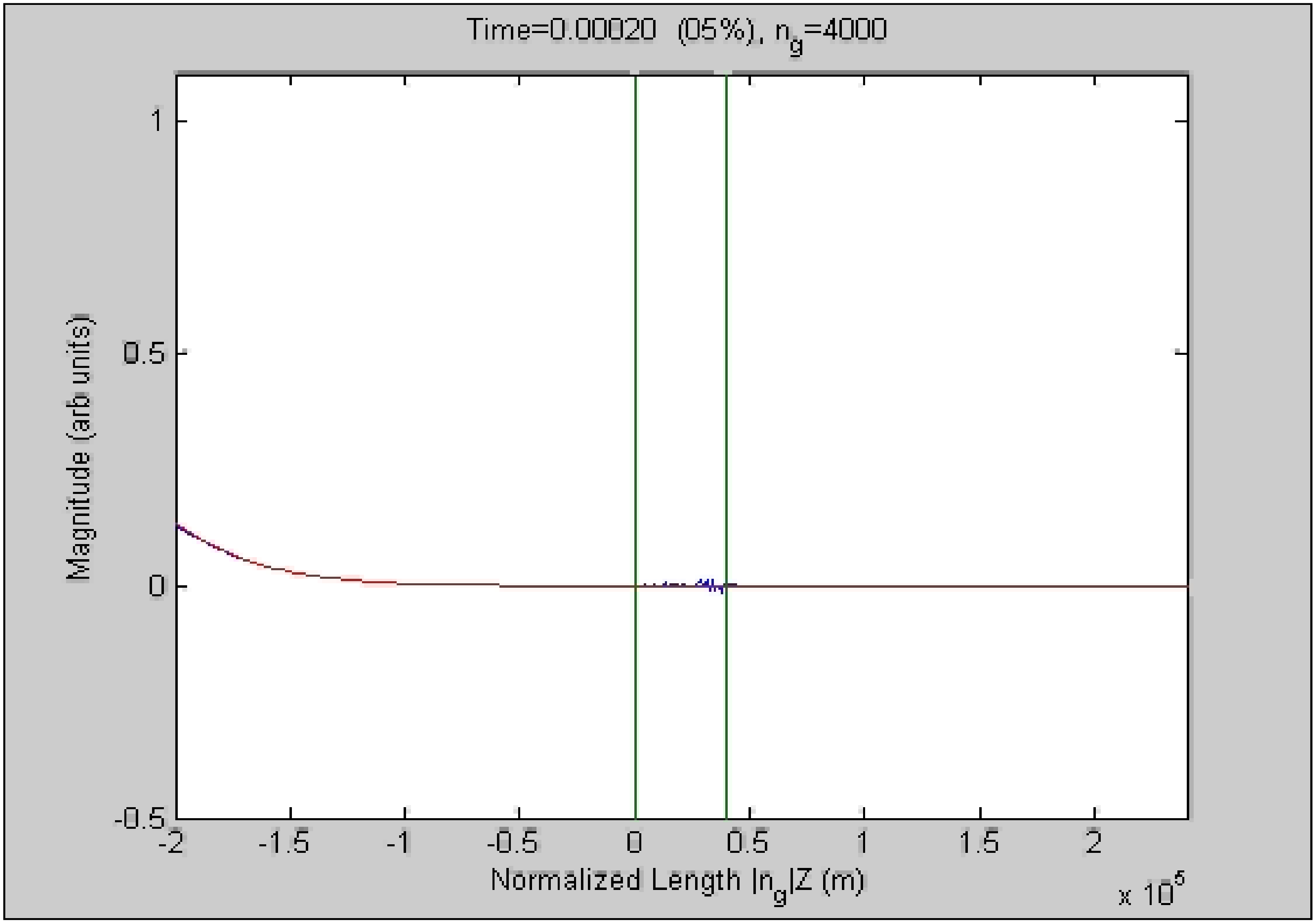
- cutback method
- couplers embedded in fiber


pulse is placed on a cw background to minimize pulse distortion

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)



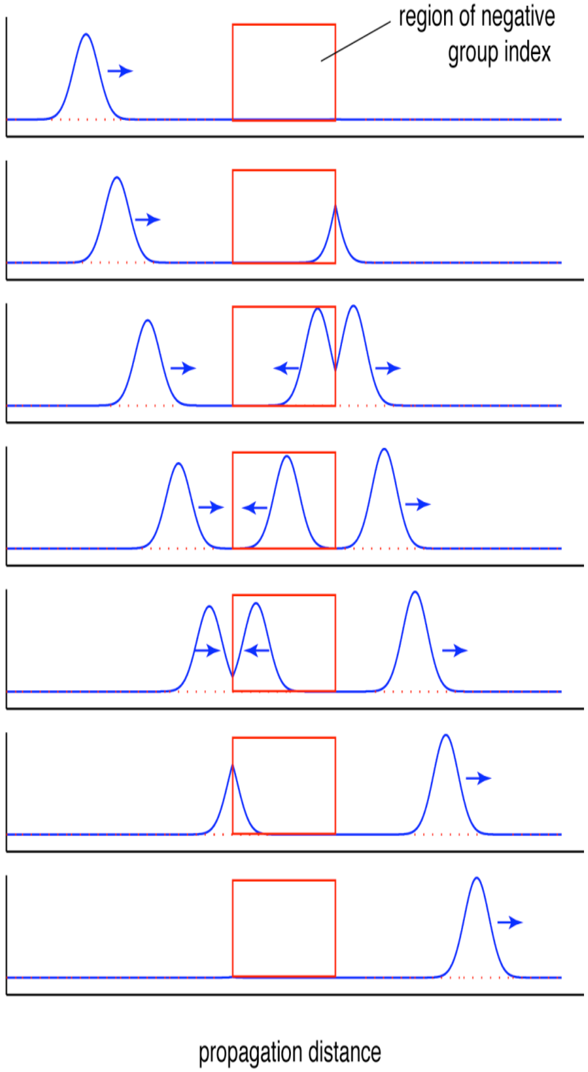
Observation of Superluminal and "Backwards" Pulse Propagation

- A strongly counterintuitive phenomenon

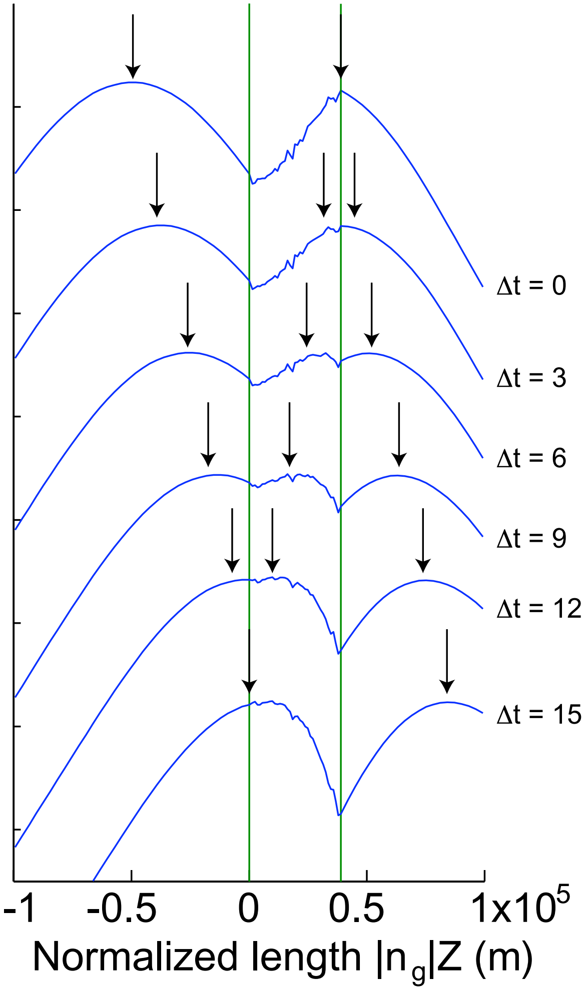
- But entirely consistent with established physics

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

\- conceptual prediction



\- laboratory results



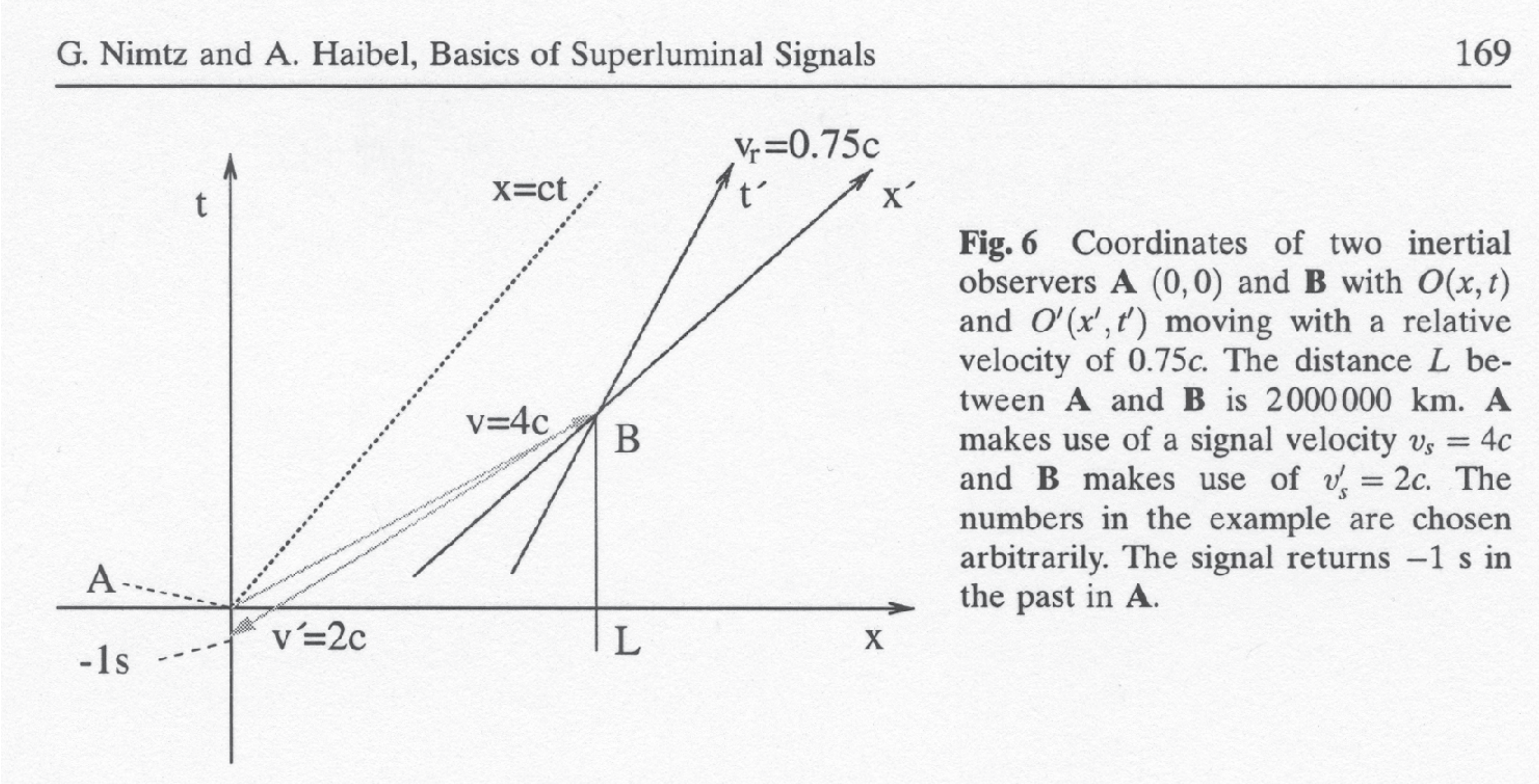
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier

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

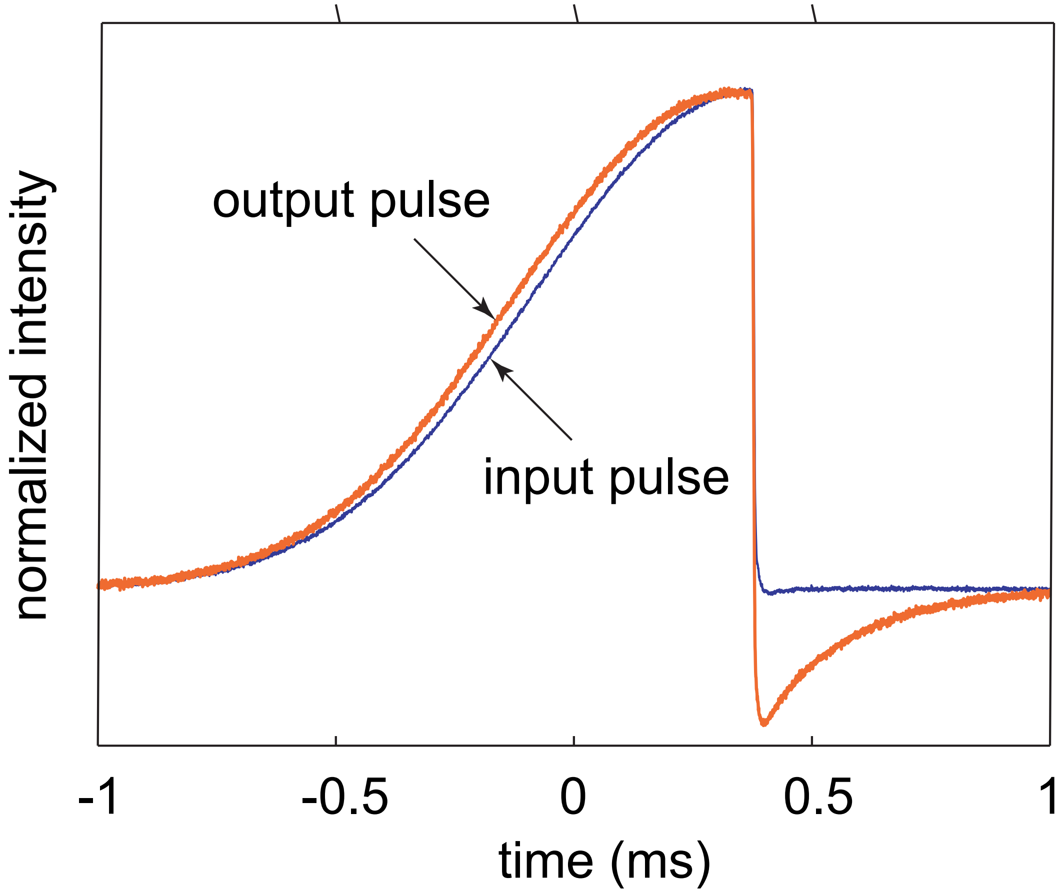


G. Nimtz and A. Haibel, Basics of Superluminal Signals 169

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 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

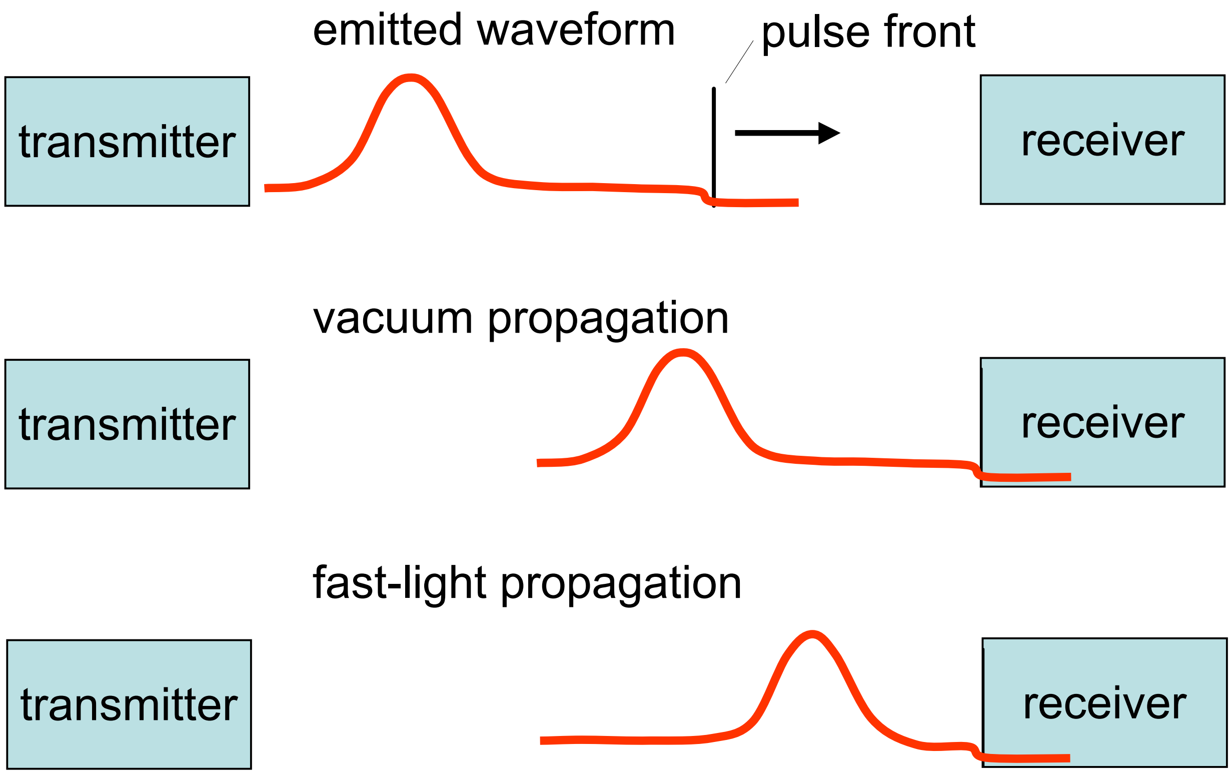
Discontinuity propagates at phase velocity

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



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

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

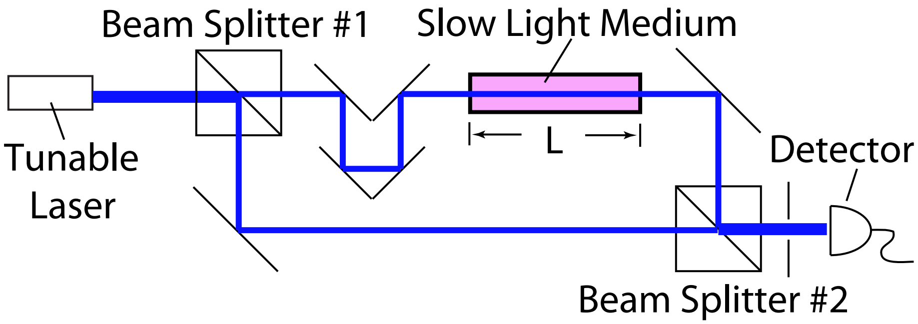
Gauthier and Boyd, Photonics Spectra, p. 82 January 2007.

Some Recent Research Results

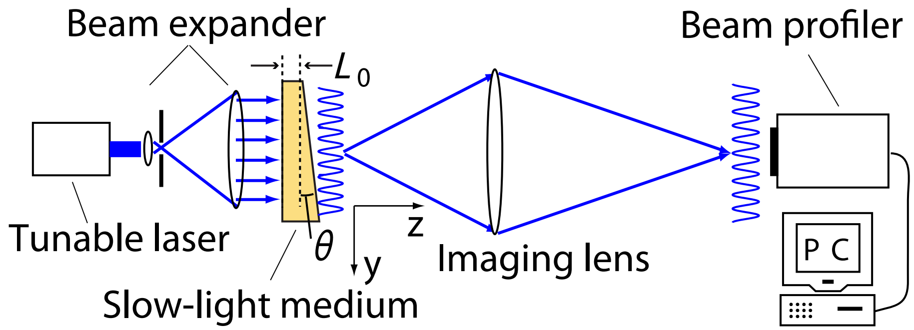
Interferometry and Slow Light

- 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

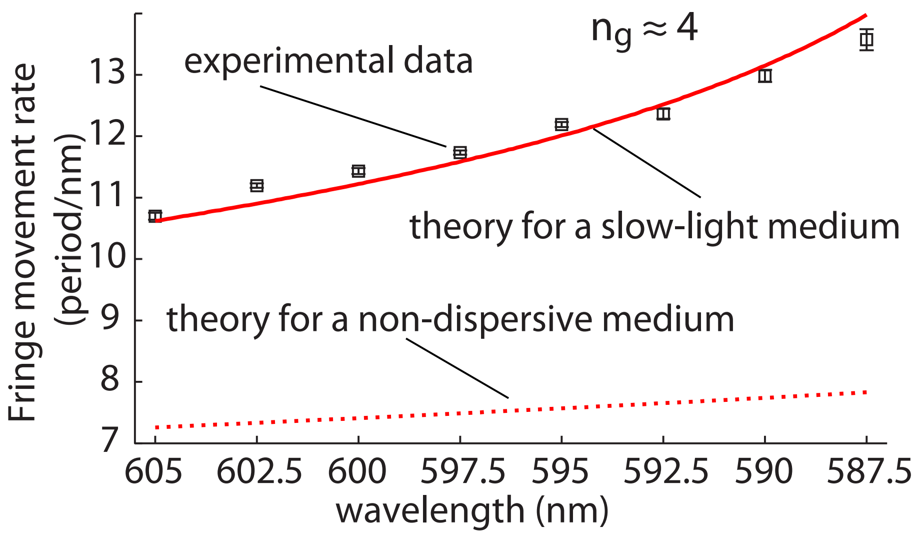


Here is why it works:

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

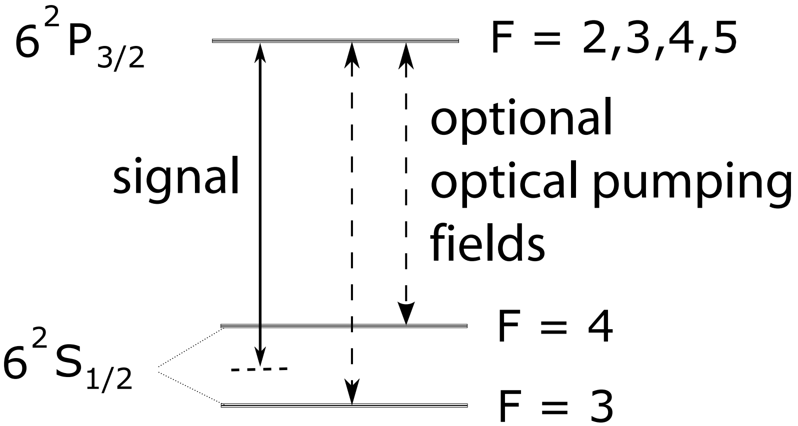
Shih et al, Opt. Lett. 2007

Our experimental results



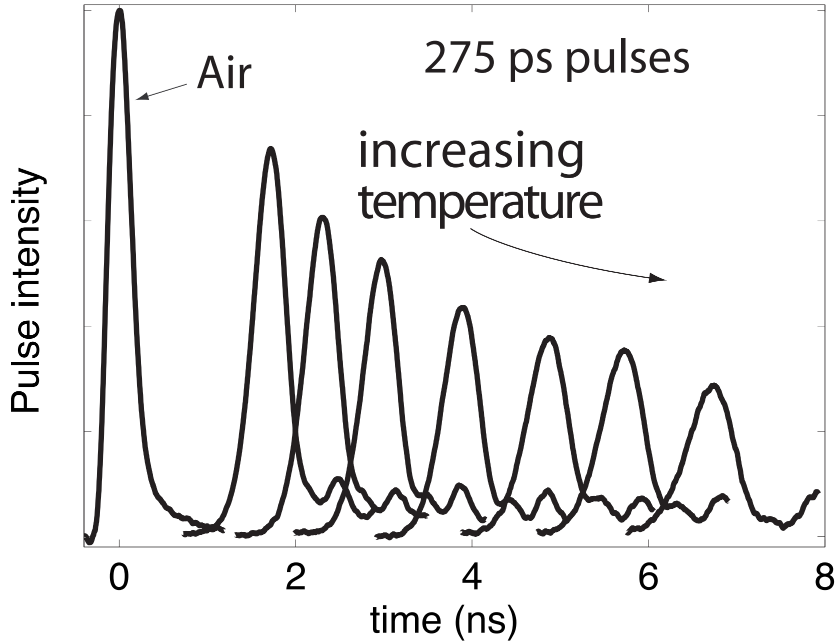
Tunable Delays of up to 80 Pulse Widths in Atomic Cesium Vapor

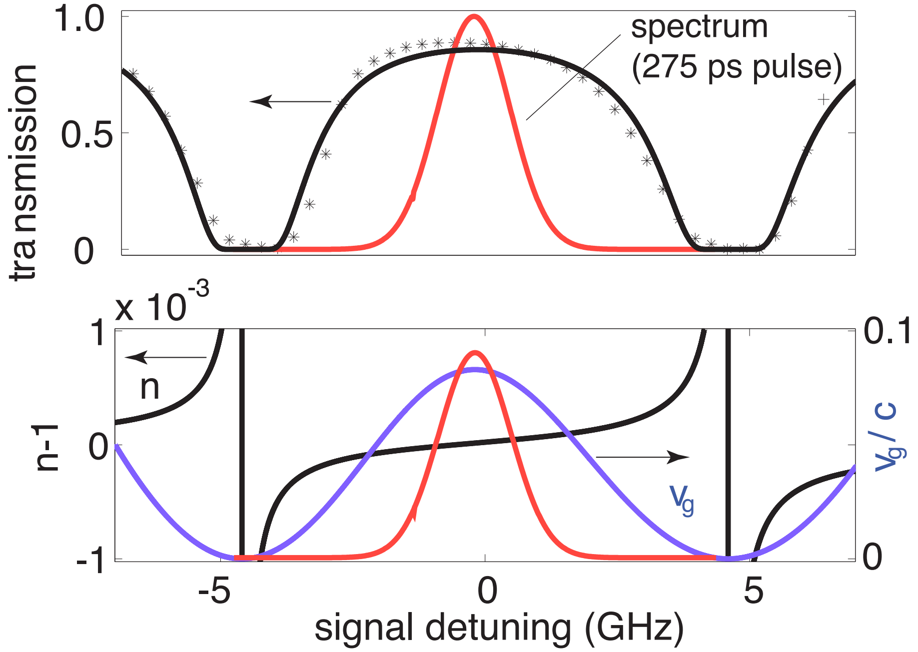
There is no delay-bandwidth product limitation on slow light!



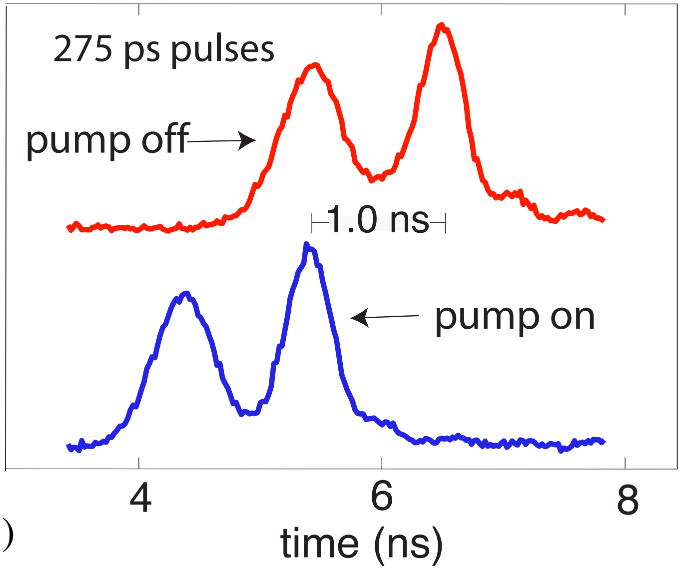
group index approximately 10 to 100

- coarse tuning: temperature



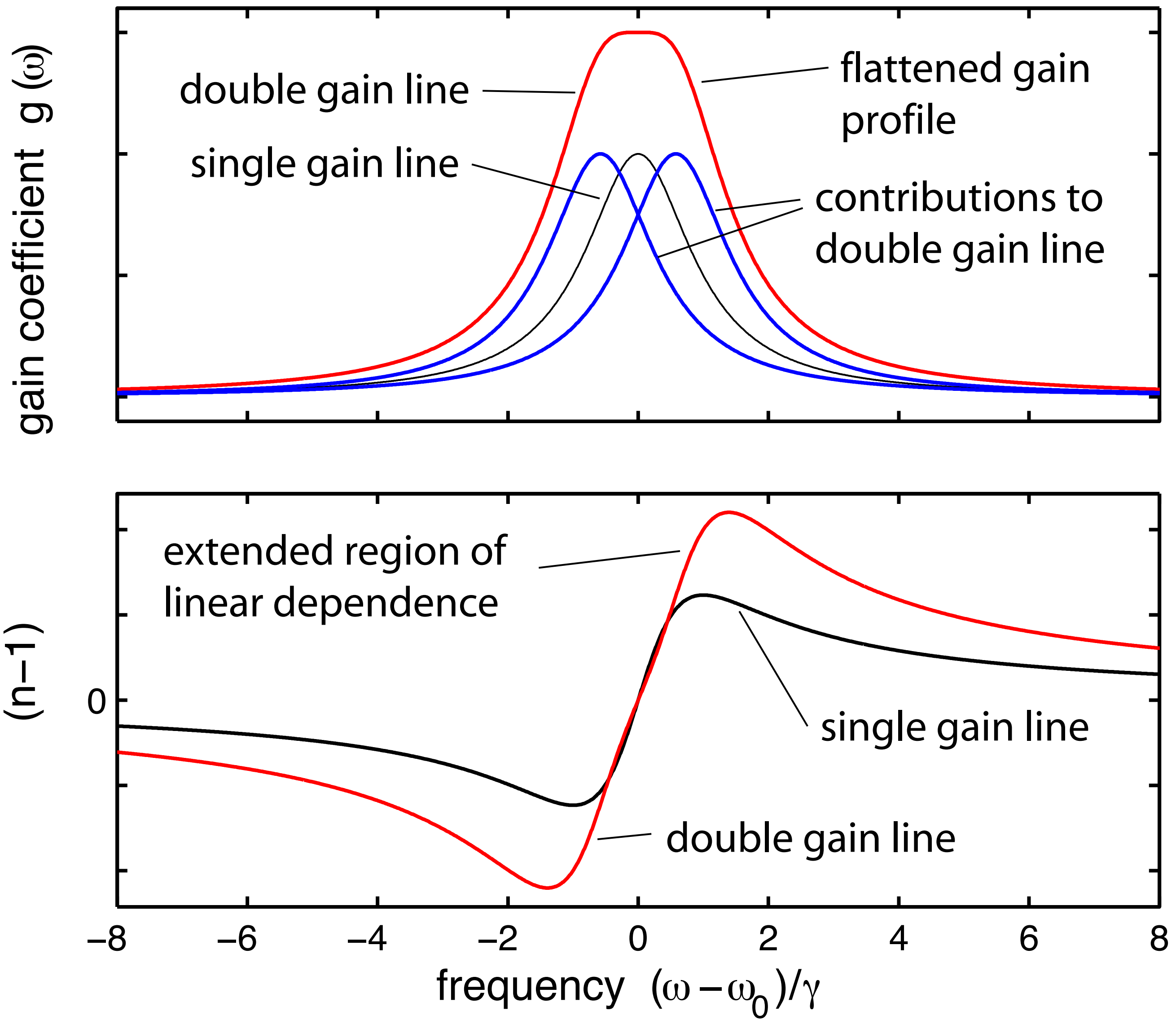


- fine tuning: optical pumping



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

Dispersion Management in Slow-Light Systems



M. D. Stenner, M. A. Neifeld, Z. Zhu, A. M. C. Dawes, and D. J. Gauthier, Optics Express 13, 9995 (2005).

Z. Shi, R. Pant, M.A. Stenner, Z. Zhu, M.D. Stenner, M.A. Neifeld, D.J. Gauthier, R.W. Boyd, Optics Letters, 32, 1986 (2007).

Dispersion Management in Slow Light Systems

	single gain line	double gain line	triple gain line	rectangular gain line
$T_d \Delta\omega$ (maximum delay-bandwidth product for single pulse)				
$G_{max} = 5$	0.45	0.9	1.15	1.7
$G_{max} = 7$	0.6	1.2	1.5	2.2
T_d / T_p(I-FWHM) (maximum fractional delay of a single pulse)				
$G_{max} = 5$	0.32	0.65	0.833	1.23
$G_{max} = 7$	0.43	0.87	1.08	1.59
$T_d / (T_{slot}/2)$ (maximum fractional delay of a pulse train as quantified by eye diagram)				
$G_{max} = 7$	0.7	1.0	1.2	2.0

G is define so that the intensity transmission is exp(G).

In all cases a criterion is imposed on the maximum allowable pulse distortion.
(5% maximum amplitude and phase distortion for single pulses; eye diagram at least 65% open)

M. D. Stenner, M. A. Neifeld, Z. Zhu, A. M. C. Dawes, and D. J. Gauthier, Optics Express 13, 9995 (2005).
Z. Shi, R. Pant, M.A. Stenner, Z. Zhu, M.D. Stenner, M.A. Neifeld, D.J. Gauthier, R.W. Boyd, Optics Letters, 32, 1986 (2007).

Break-Out Session on Slow and Fast Light

Paul Narum, *The Norwegian Defence Research Establishment*
‘‘Fast and slow light - What are the fundamental limitations and what does it actually mean?’’

Daniel J. Gauthier, *Duke University*
‘‘Observation of Stored Light via Stimulated Brillouin Scattering’’

John Howell, *University of Rochester*
‘‘Slow and Stopped Images’’

George R. Welch, *Texas A&M University*
‘‘Subwavelength imaging via dark states’’

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.

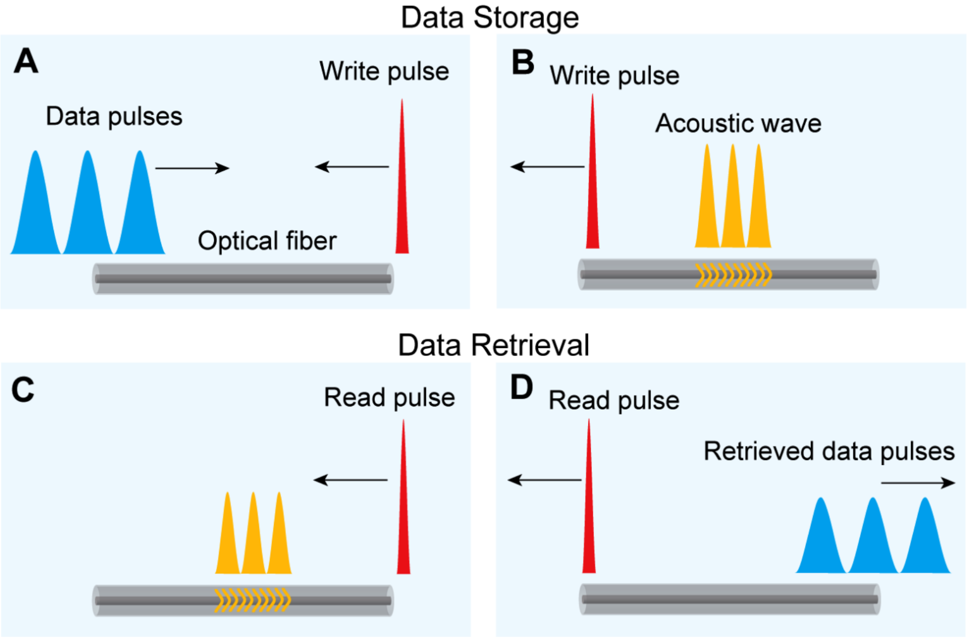
Why are the two cases so different?**

* 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.

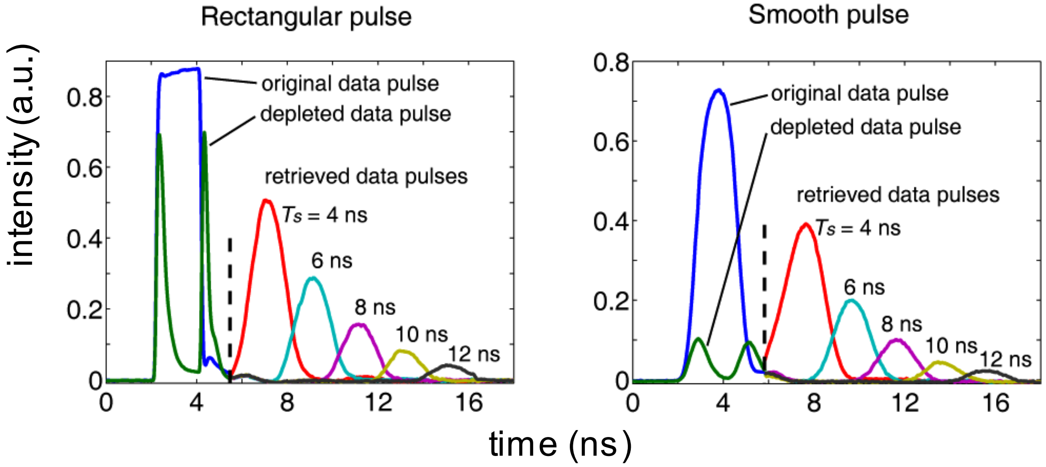
Stored Light via SBS *(Duke/Rochester effort)*

The Concept: Convert information encoded on an optical wave into an acoustic wave via stimulated Brillouin scattering. A read out pulse converts the acoustic wave back to the optical domain.



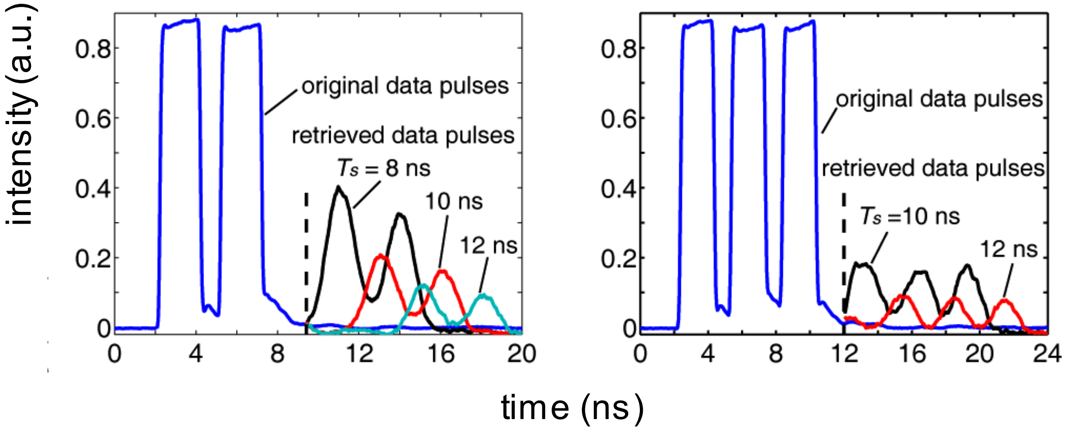
Experimental Results

single-pulse storage and retrieval


Rectangular pulse

Smooth pulse

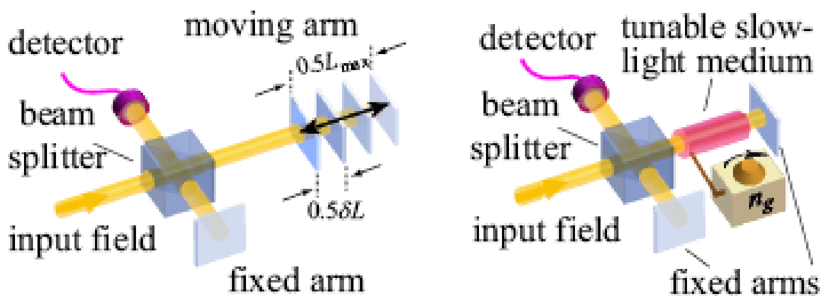
multiple-pulse storage and retrieval

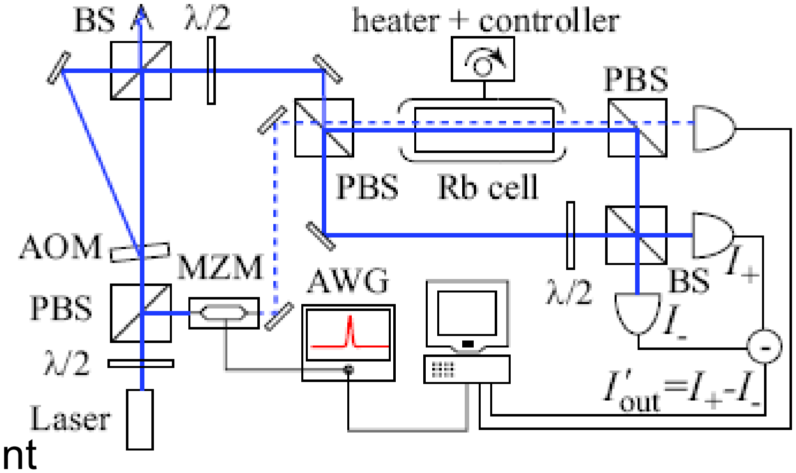


Phase II milestone for stored light via SBS is essentially achieved

Howell-Boyd Collaboration

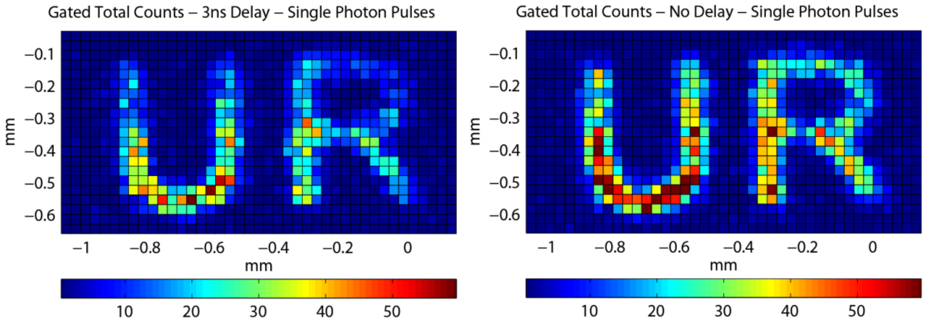
I. Slow Light Fourier Transform Interferometry

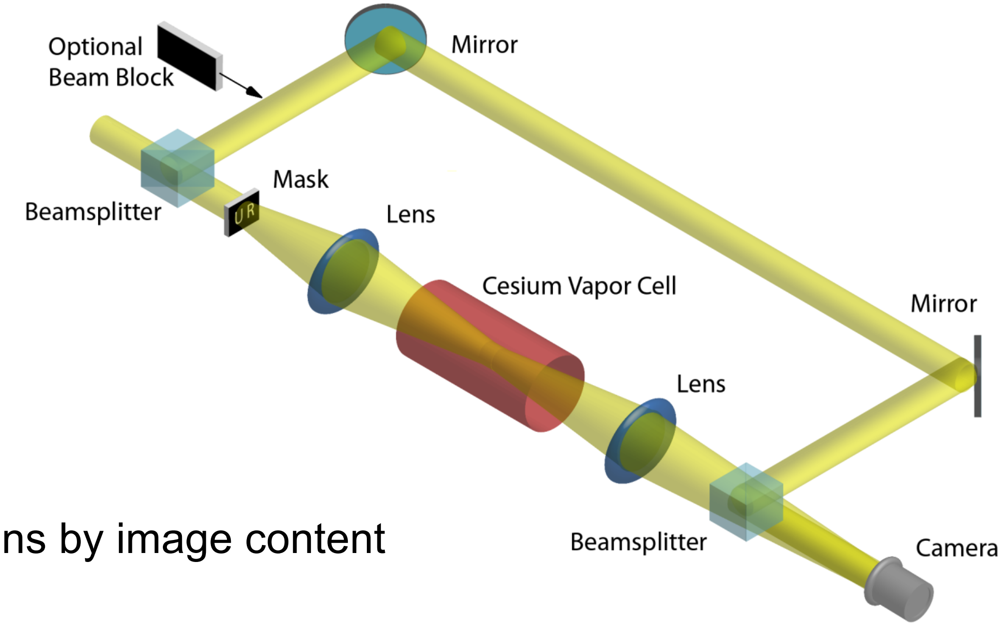




We have now achieved a 100X resolution enhancement

II. Imaging Through a Slow-Light Medium





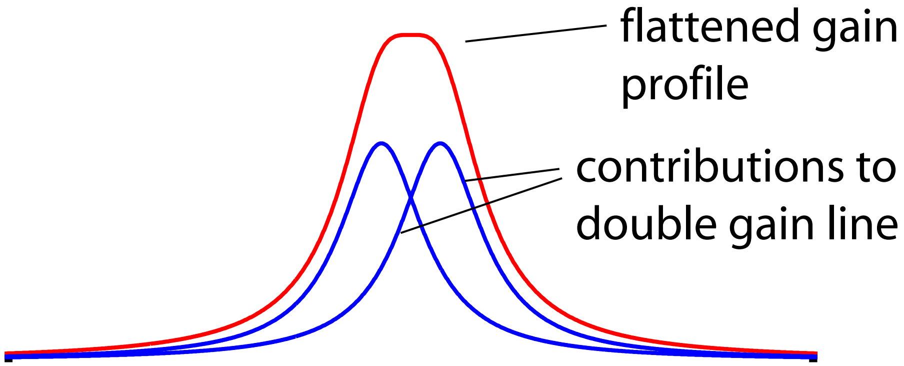
Currently working on sorting of individual photons by image content

Take-Away Message

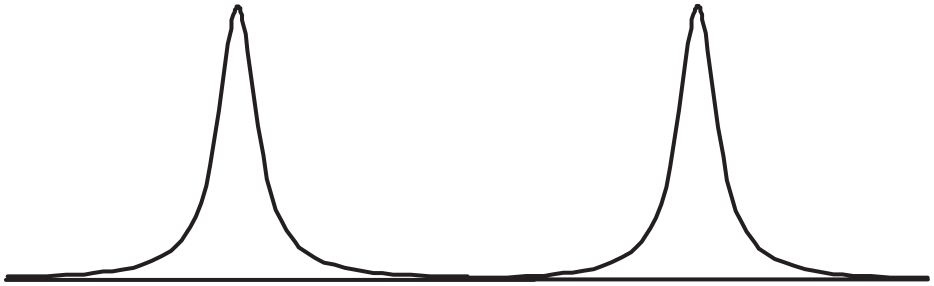
Properties of slow-light systems can be dramatically improved by using non-Lorentzian gain/absorption line shapes.

Improvement can be realized both through use of

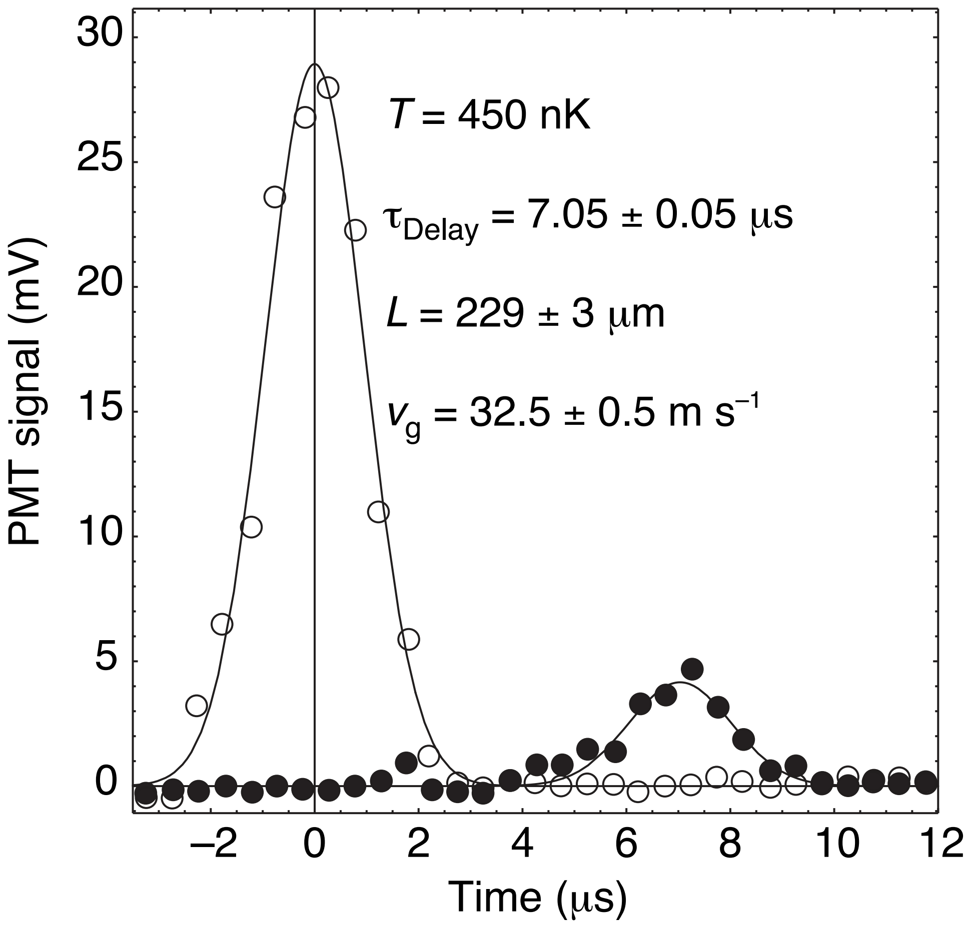
– overlapping Lorentzians



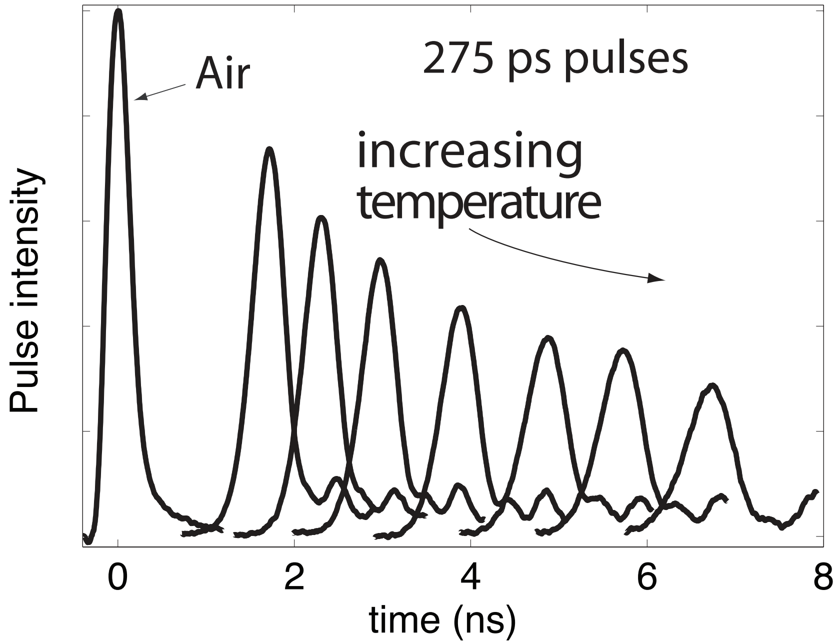
– separated absoprtion lines



Summary – Progress in Slow-Light Research

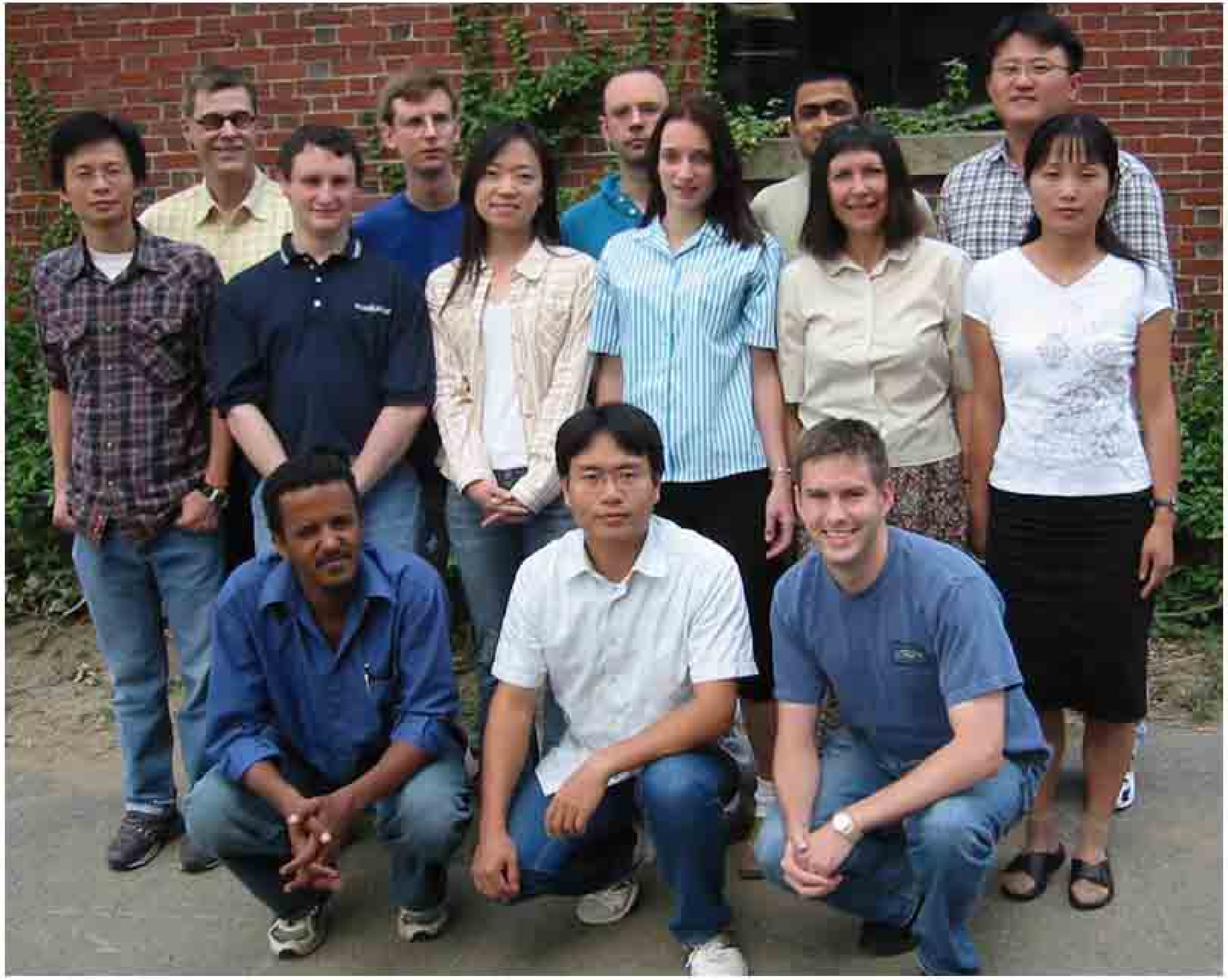


Delay of 3 pulse widths (1999)
Results of Hau, L



Delay of 80 pulse widths (2007)
Results of Howell

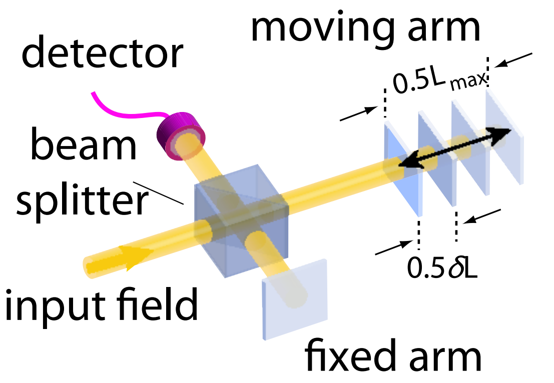
Special Thanks to My Students and Research Associates



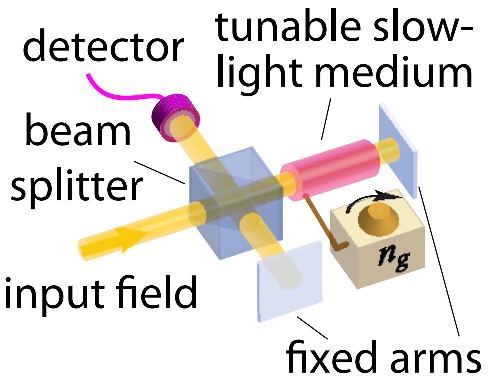
Thank you for your attention!

High-Resolution Slow-Light Fourier Transform Interferometer

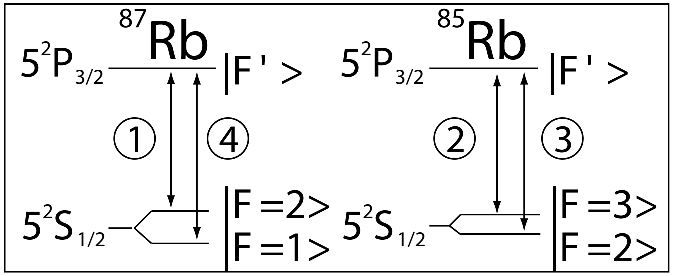
Conventional FT Interferometer



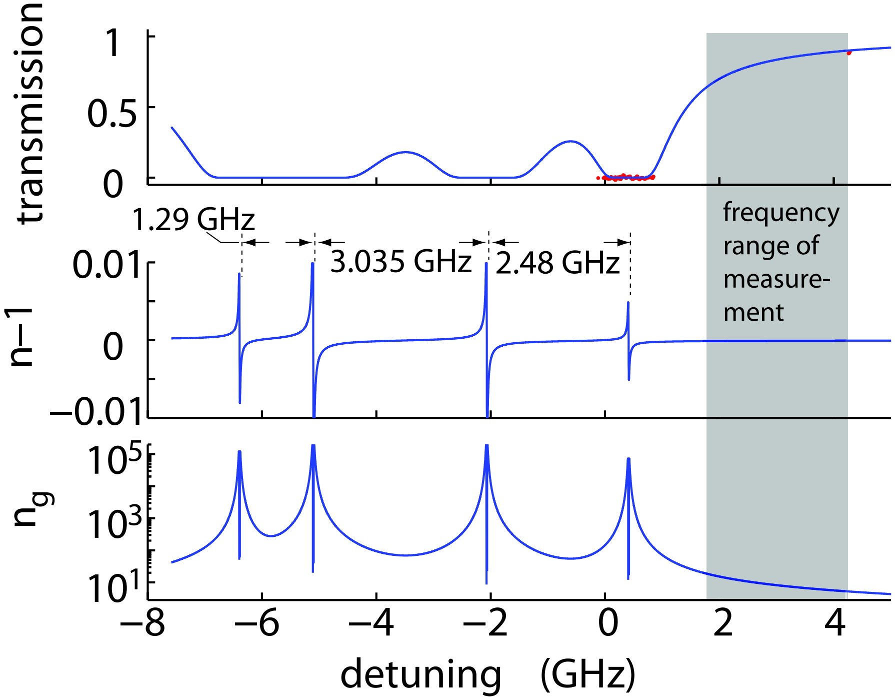
Slow-light FT Interferometer



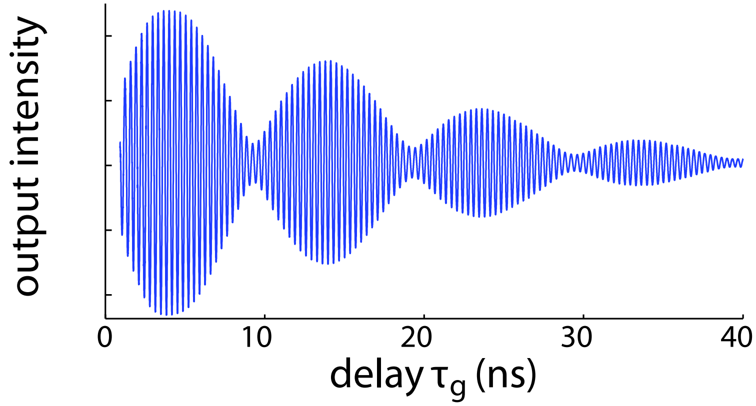
Energy Levels

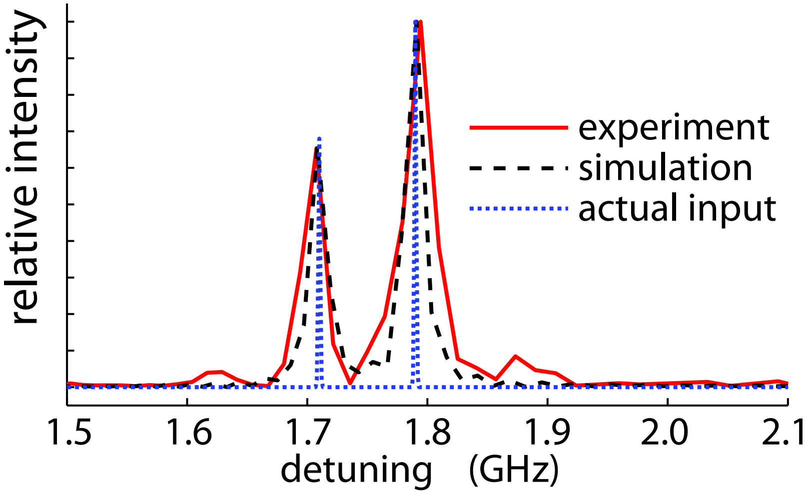


Theoretical Model



Results





Shi, Boyd, Camacho, Setu, and Howell

How to Prevent Pulse Distortion (which can limit data rates)

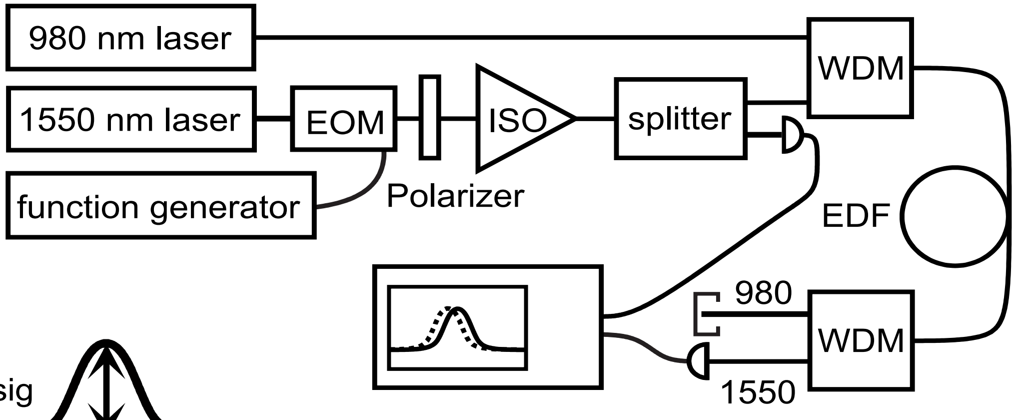
Pulse-on-Background Method

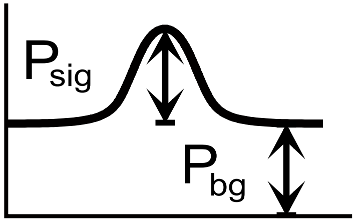
Two primary mechanisms for pulse distortion in an EDFA

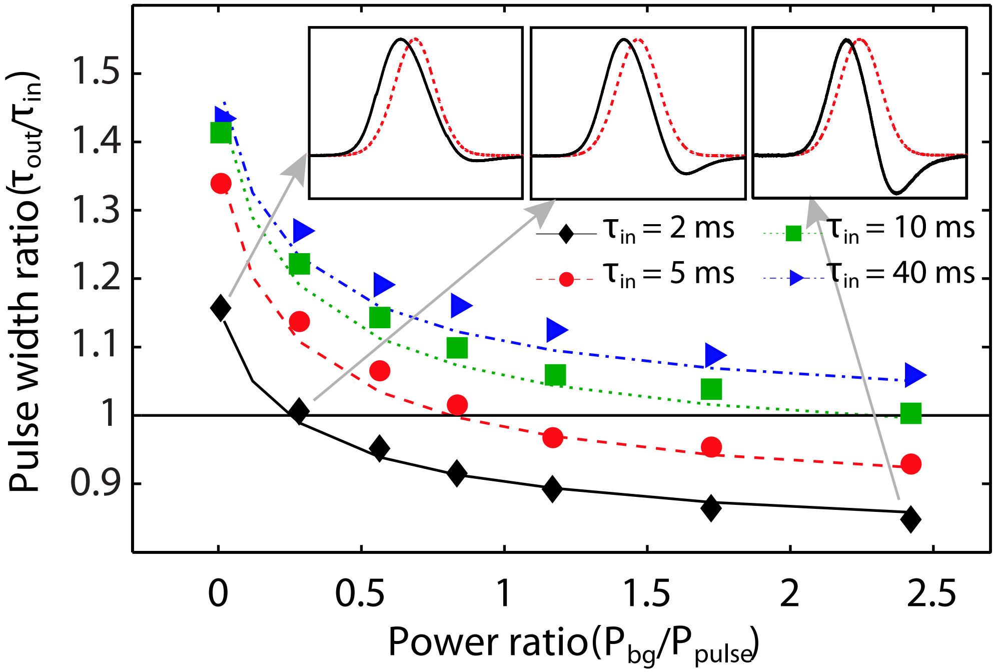
- – Spectral broadening, leading to temporal compression
- – Temporal gain recovery, leading to temporal broadening

For long pulses, the trailing edge experiences reduced saturation. This effect is minimized by adding a cw background to reduce gain recovery.

For the optimum ratio of pulse-to-background power, the two effects exactly cancel !





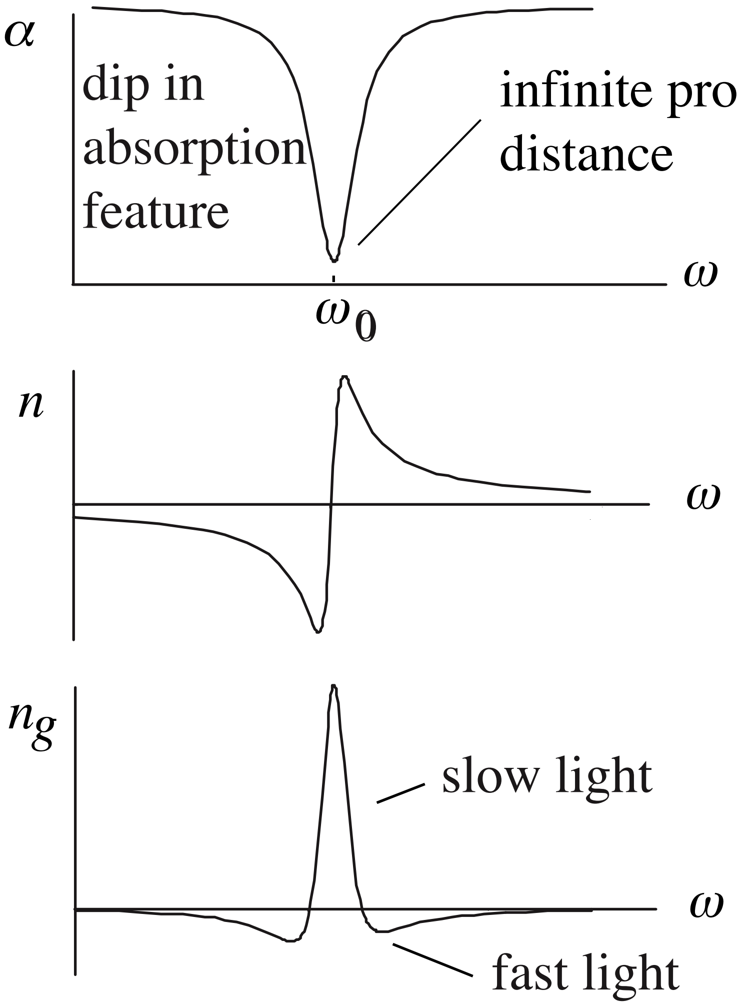


Shin et al., Opt. Lett. **32**, 906 (2007).

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.

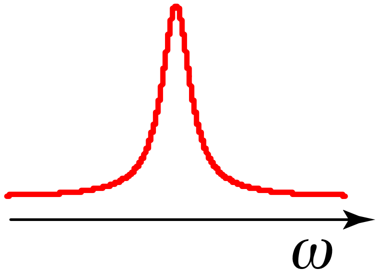
This “trick”works only for slow light.



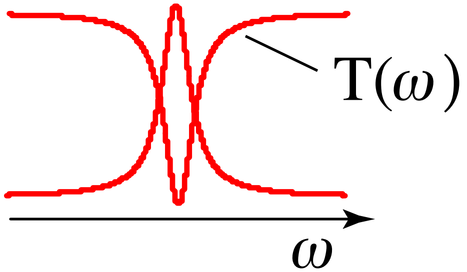
Influence of Spectral Reshaping

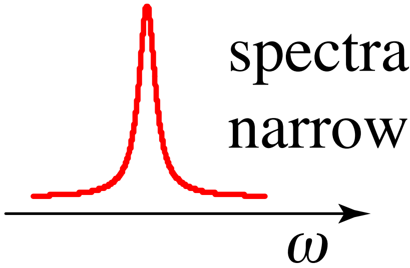
(Line-Center Operation, Dip in Gain or Absorption Feature)

input pulse



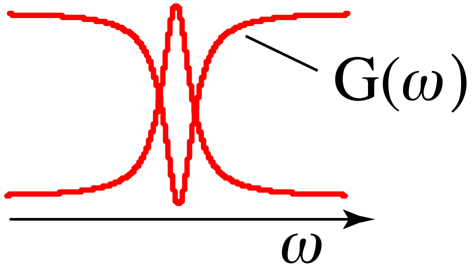
output pulse
slow-light

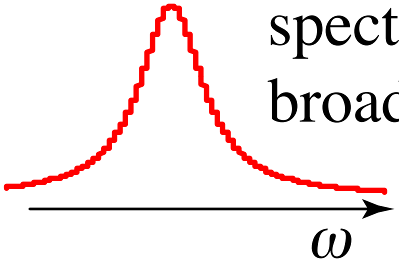




spectrally
narrowed pulse

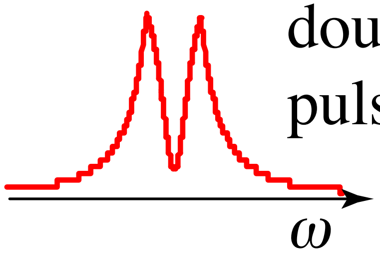
output pulse
fast-light





spectrally
broadened pulse

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

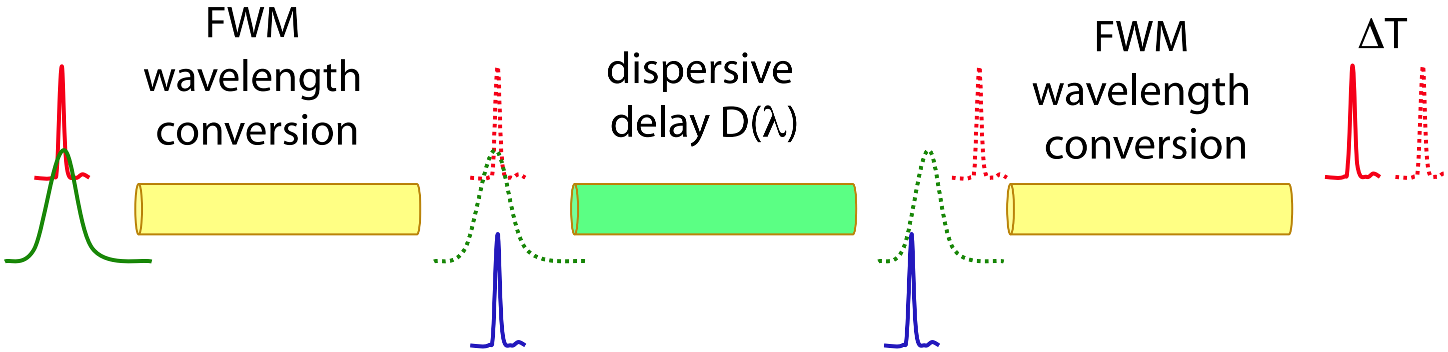


double-humped
pulse

Slow-Light Telecom Buffer / Regeneration System

- Optical Buffering – Need many pulse-widths of delay

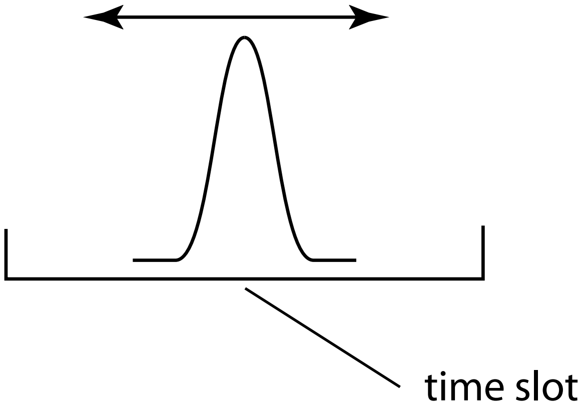
  Use the conversion / dispersion method of Gaeta and others

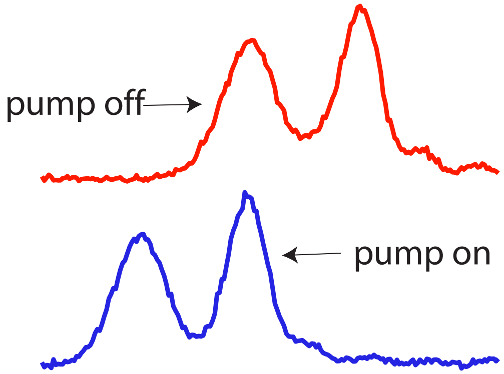


- Regeneration of Pulse Timing –

  Single pulse-width of delay adequate, but need precise control

  Use "true" slow light (SBS?)





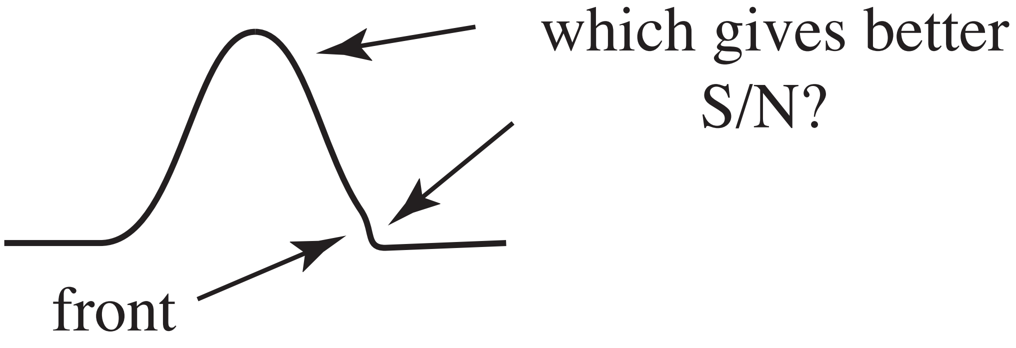
Information Velocity – Tentative Conclusions

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.

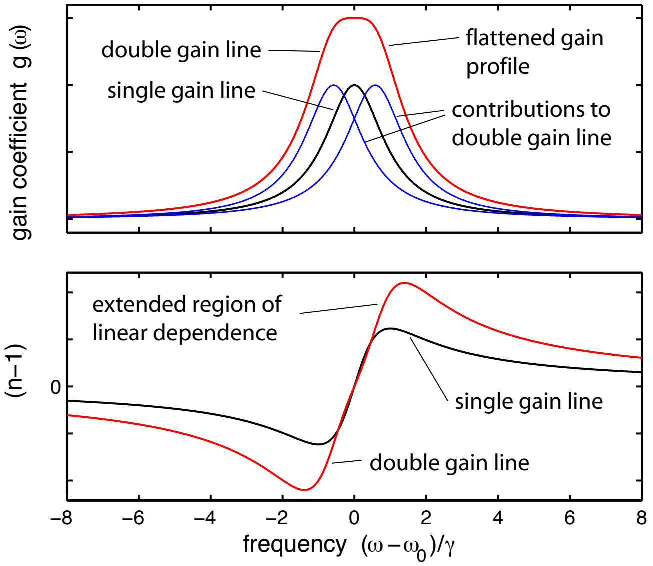
In this sense, useful information often propagates at the group velocity.

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.

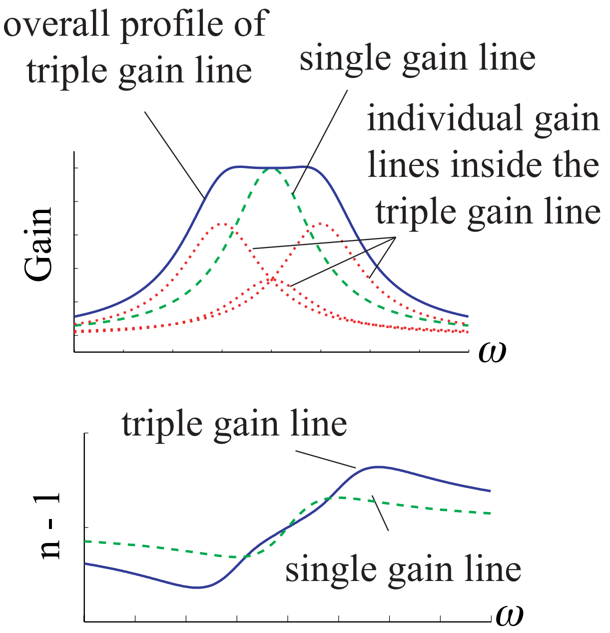


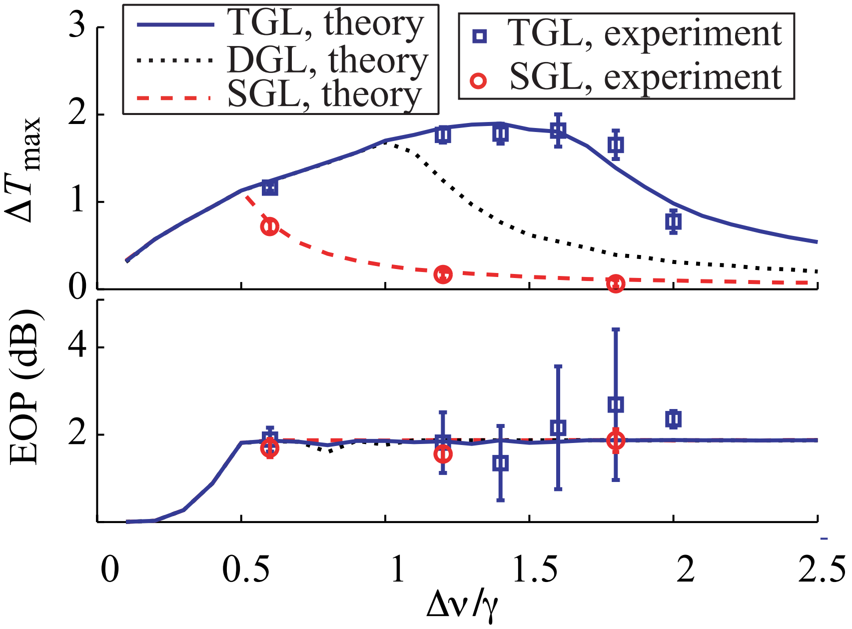
Dispersion Management in Slow Light Systems

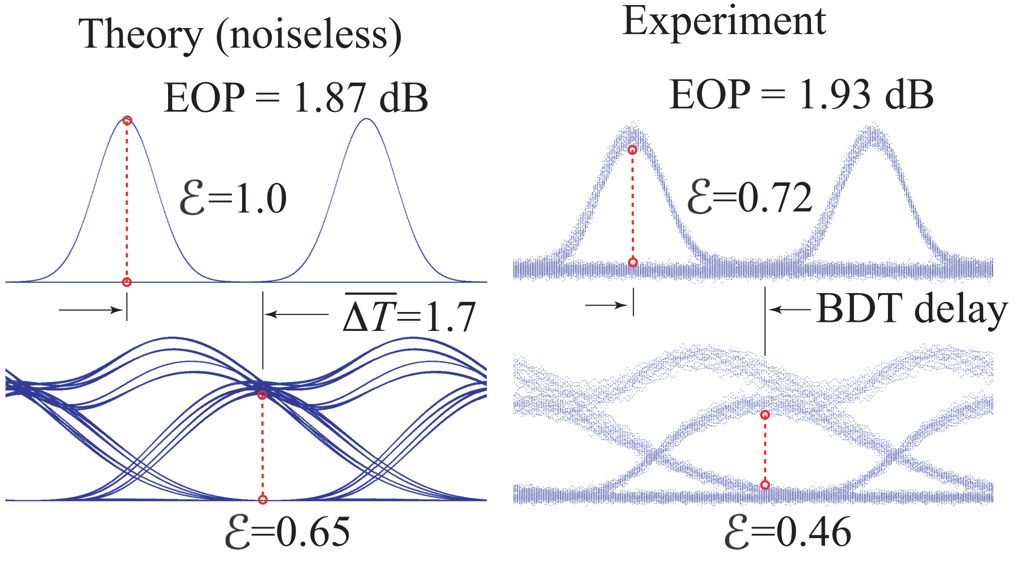
- Double Gain Line



- Triple Gain Line







M. D. Stenner, M. A. Neifeld, Z. Zhu, A. M. C. Dawes, and D. J. Gauthier, Optics Express 13, 9995 (2005).

Z. Shi, R. Pant, M.A. Stenner, Z. Zhu, M.D. Stenner, M.A. Neifeld, D.J. Gauthier, R.W. Boyd, Optics Letters, 32, 1986 (2007).