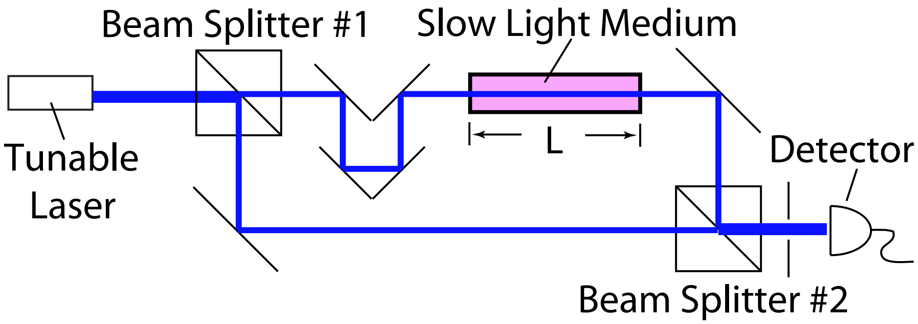
Brief Research Update

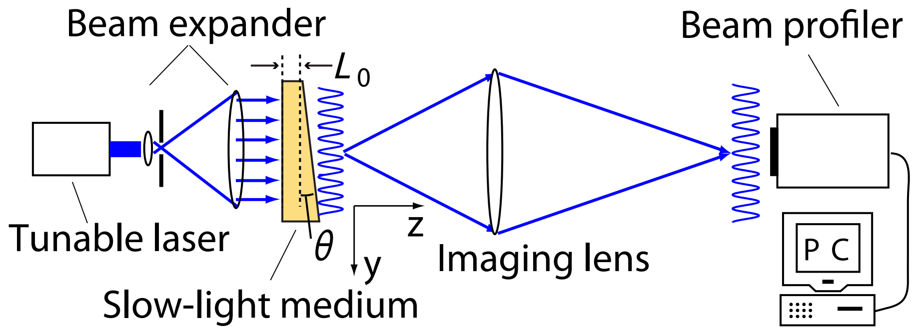
Interferometry and Slow Light

- 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

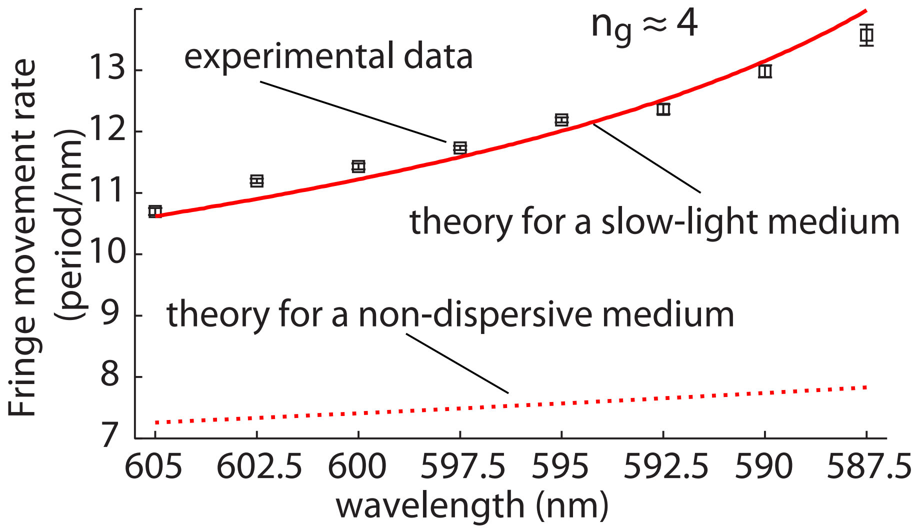


Here is why it works:

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

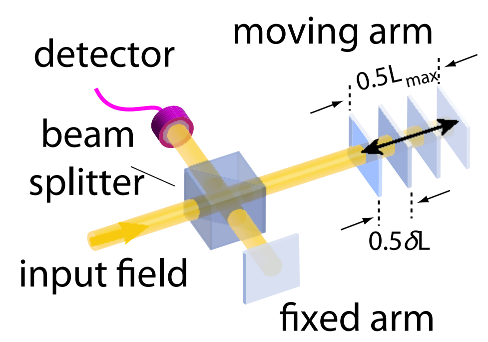
Shih et al, Opt. Lett. 2007

Our experimental results

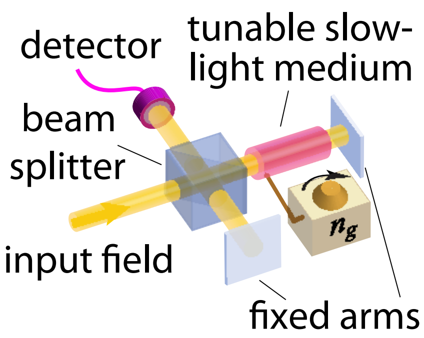


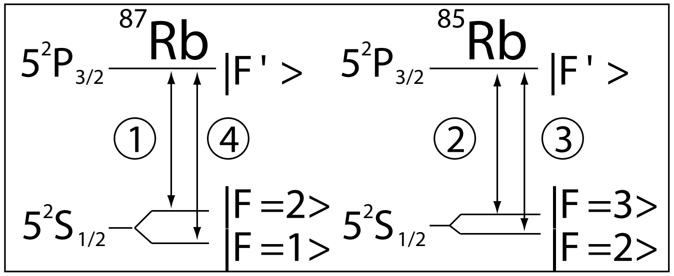
High-Resolution Slow-Light Fourier Transform Interferometer

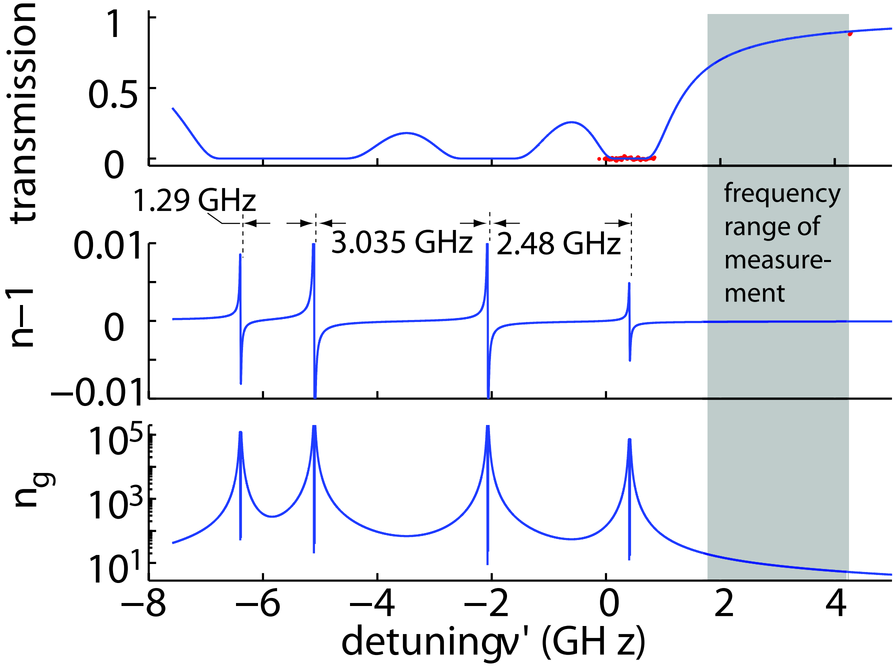
conventional FT Interferometer

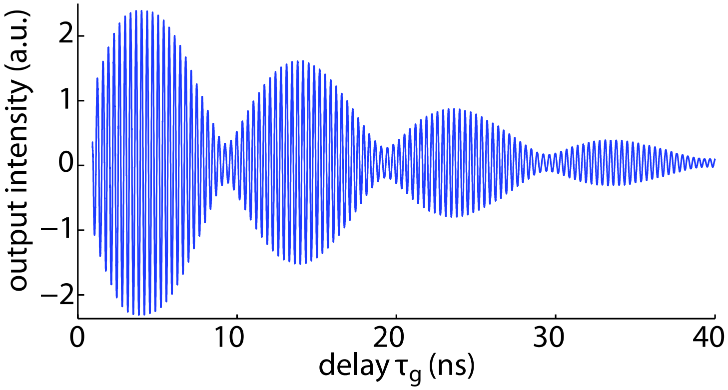


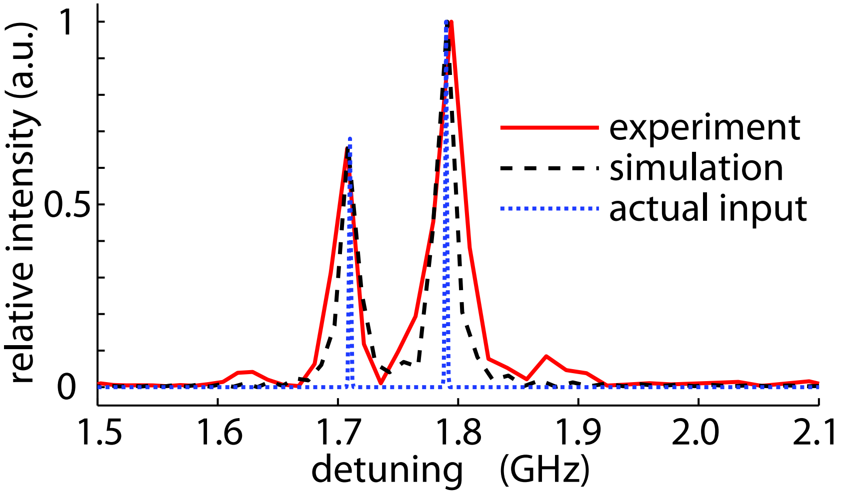
slow-light FT Interferometer







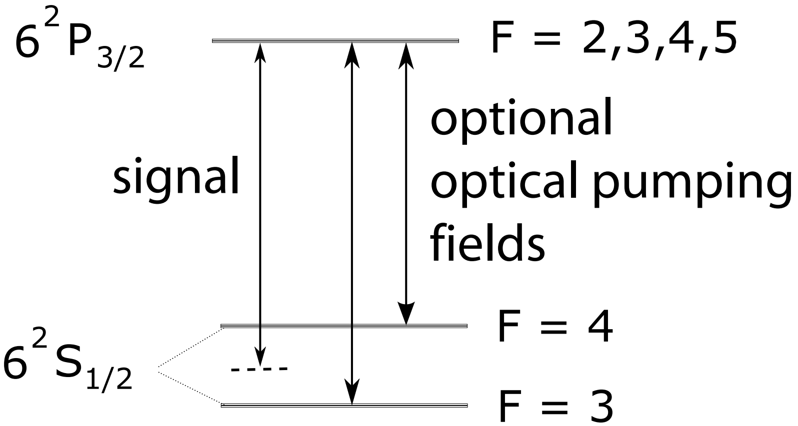




Shi, Boyd, Camacho, Setu, and Howell

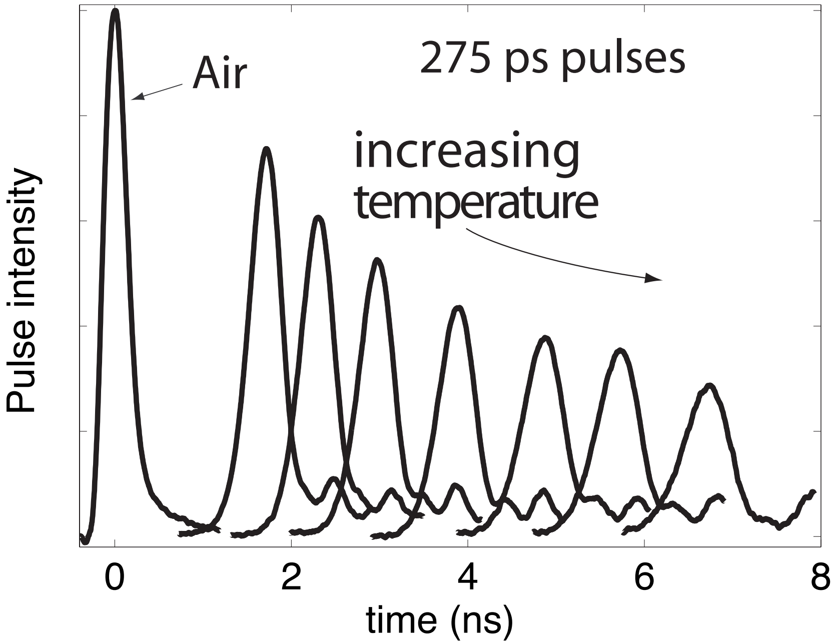
Tunable Delays of up to 80 Pulse Widths in Atomic Cesium Vapor

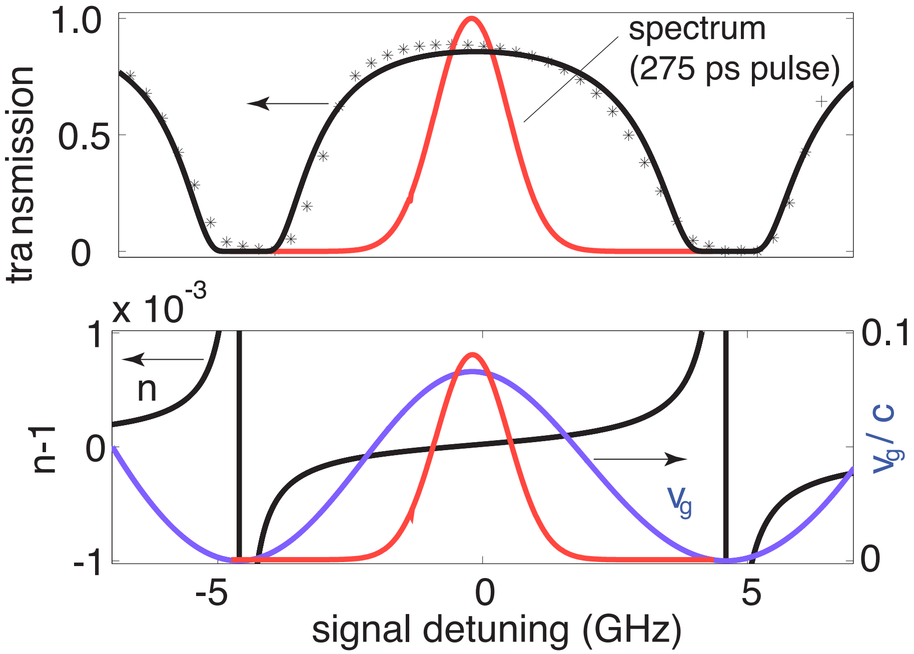
There is no delay-bandwidth product limitation on slow light!



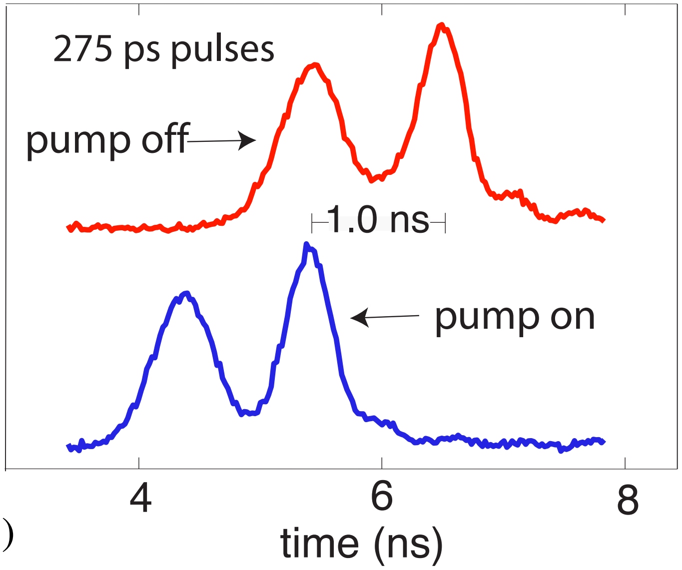
group index approximately 10 to 100

- coarse tuning: temperature





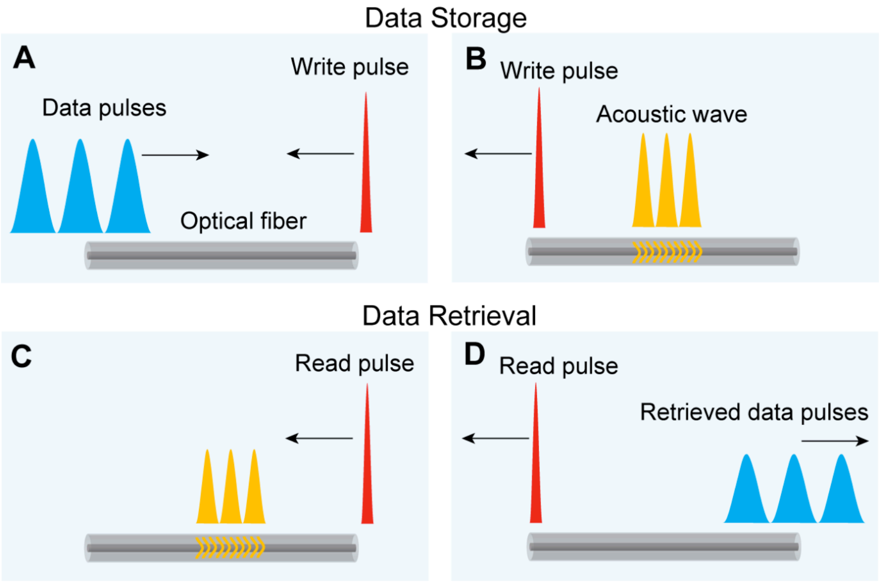
- fine tuning: optical pumping



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

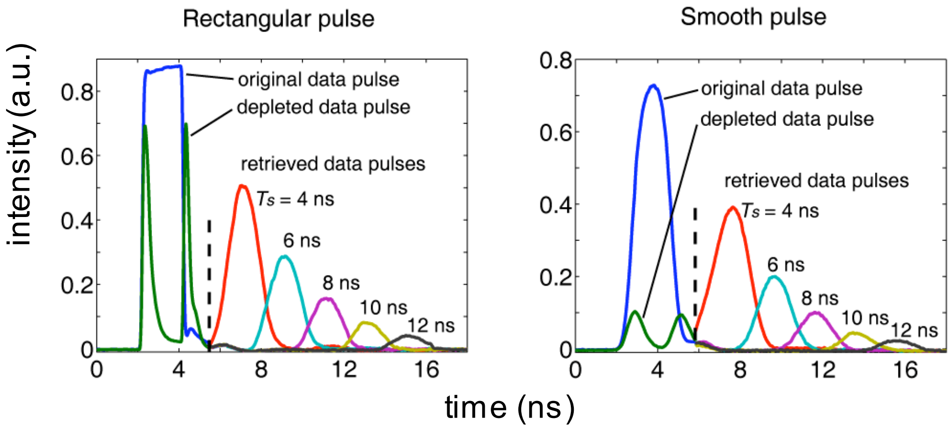
Stored Light via SBS *(Duke/Rochester effort)*

The Concept: Covert 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.

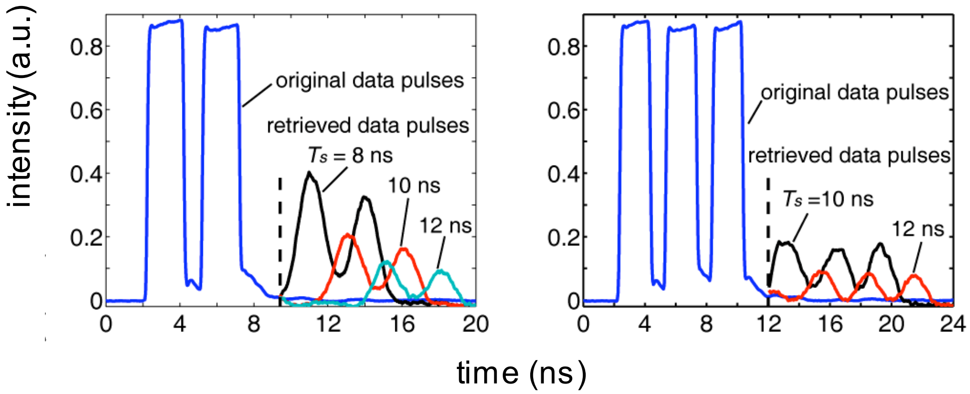


Experimental Results

single-pulse storage and retrieval

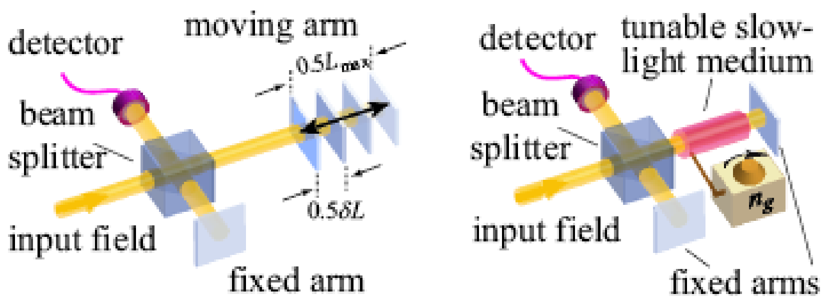


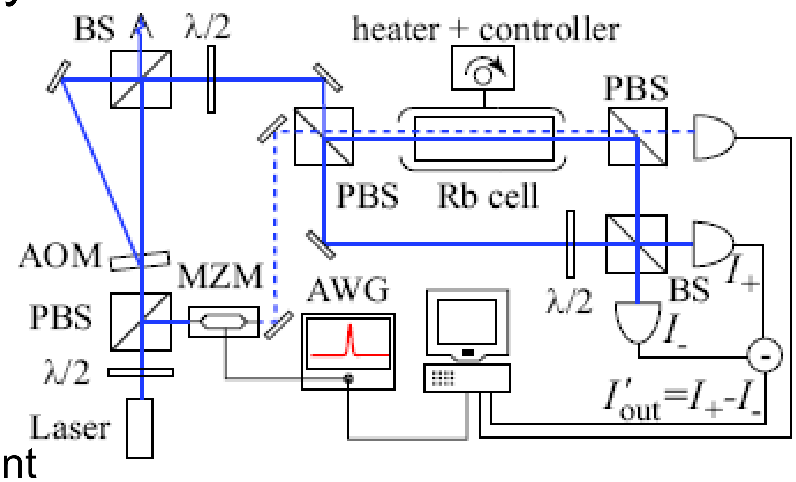
multiple-pulse storage and retrieval



Phase II milestone for stored light via SBS is essentially achieved

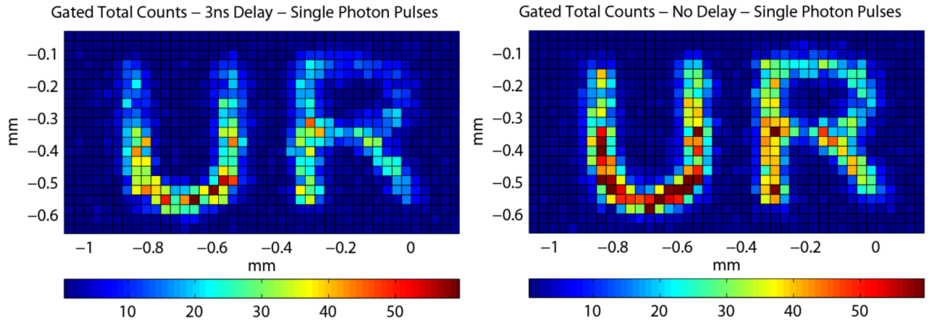
I. Slow Light Fourier Transform Interferometry

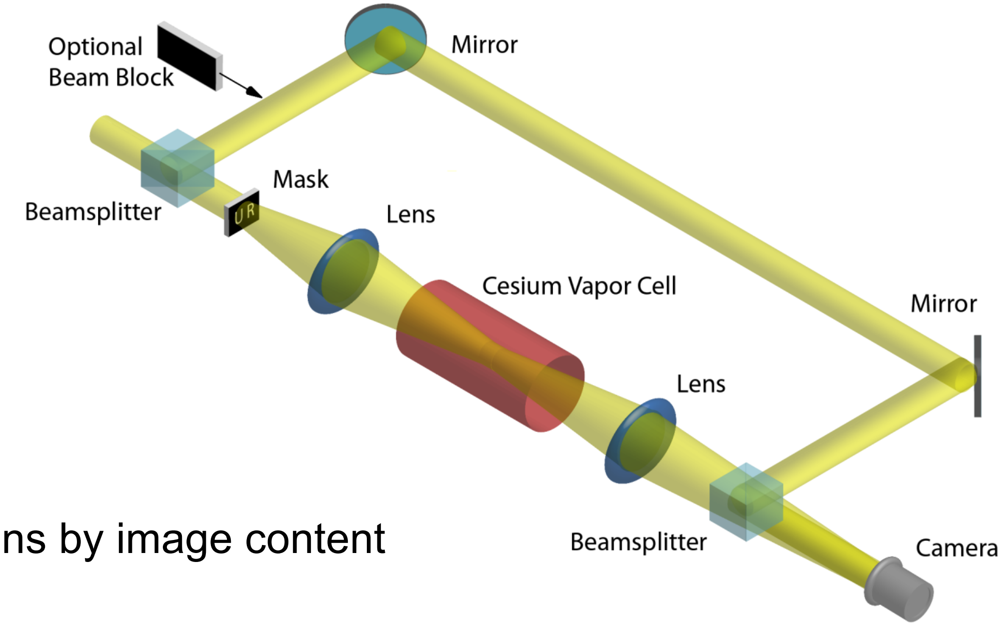




We have now achieved a 100X resolution enhancement

II. Imaging Through a Slow-Light Medium





Currently working on sorting of individual photons by image content

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

Robert W. Boyd

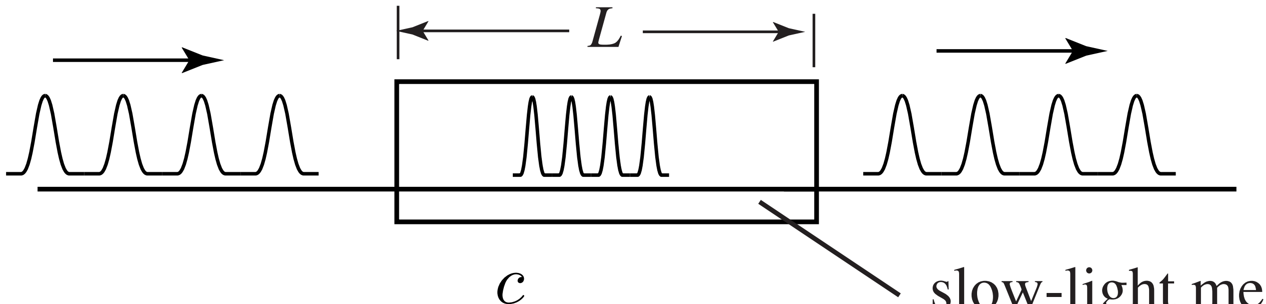
Institute of Optics and
Department of Physics and Astronomy
University of Rochester

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

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



slow-light medium, $n_g >> 1$

group velocity: $v_g = \frac{c}{n_g}$

group index: $n_g = n + \omega \frac{dn}{d\omega}$

group delay: $T_g = \frac{L}{v_g} = \frac{L n_g}{c}$

controllable delay: $T_{\text{del}} = T_g - L/c = \frac{L}{c}(n_g - 1)$

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
≈ information storage capacity of medium

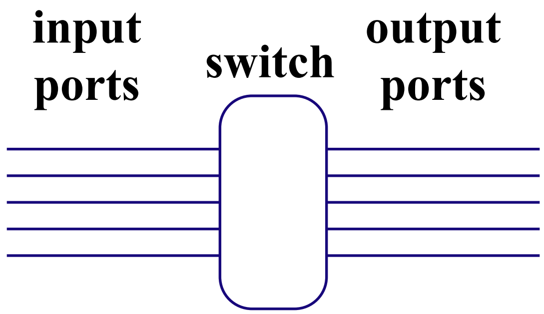
Best result to date: delay by 4 pulse lengths (Kasapi et al. 1995)

But data packets used in telecommunications contain ≈ 10^3 bits

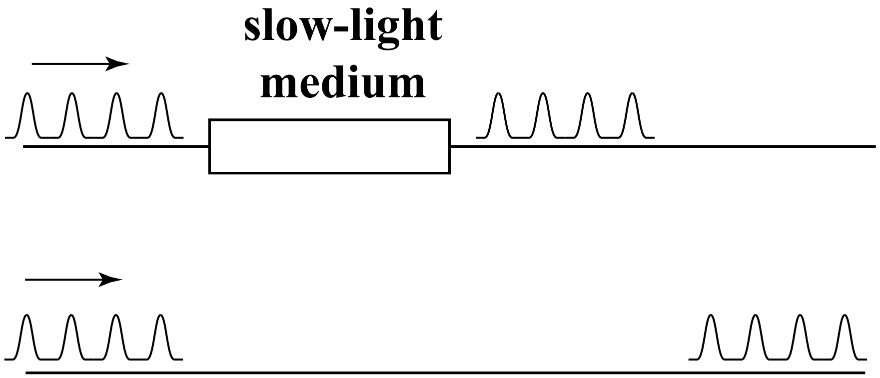
What are the prospects for obtaining slow-light delay lines with 10^3 bits capacity?

Slow Light and Optical Buffers

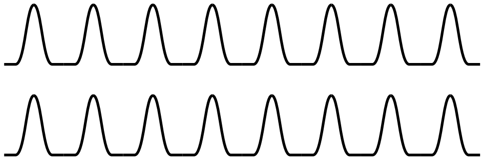
All-Optical Switch



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

Slow Light in Optical Fibers:
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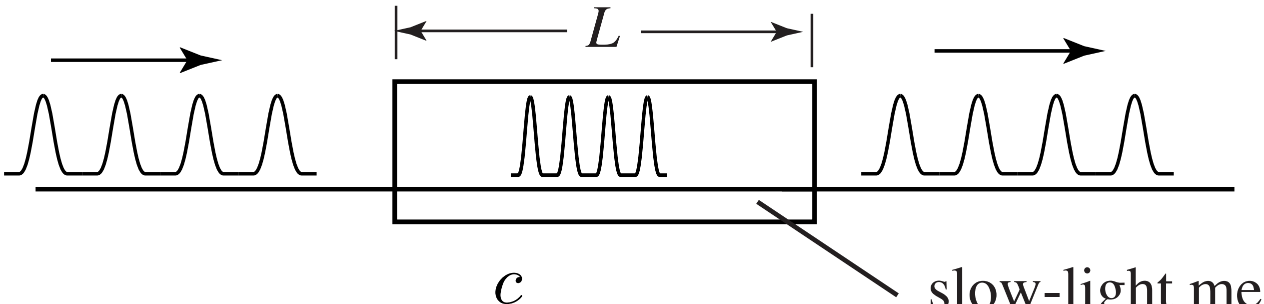

group velocity: $v_g = \dfrac{c}{n_g}$

group index: $n_g = n + \omega \dfrac{dn}{d\omega}$

group delay: $T_g = \dfrac{L}{v_g} = \dfrac{L n_g}{c}$

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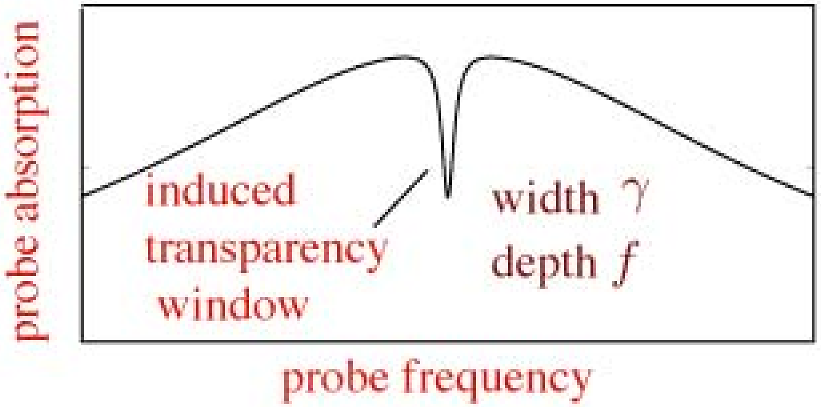
To make controllable delay as large as possible:

- make *L* as large as possible (reduce residual absorption)
- maximize the group index

Generic Model of EIT and CPO Slow-Light Systems



probe absorption

$$\alpha(\delta) = \alpha_0 \left(1 - \frac{f}{1 + \delta^2/\gamma^2}\right) \approx \alpha_0 \left[(1 - f) - f\frac{\delta^2}{\gamma^2}\right] \text{ where } \quad \delta = \omega - \omega_0$$

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

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

normalized induced delay (T_0 = pulse width)

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

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

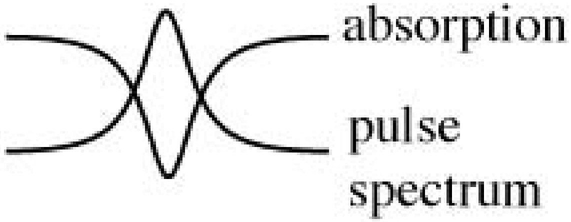
Limitation 2: Group velocity dispersion

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

$$\left(\frac{T_{\rm del}}{T_0}\right)_{\rm max} = \frac{3}{2}\gamma T_0,$$

which has no upper bound.

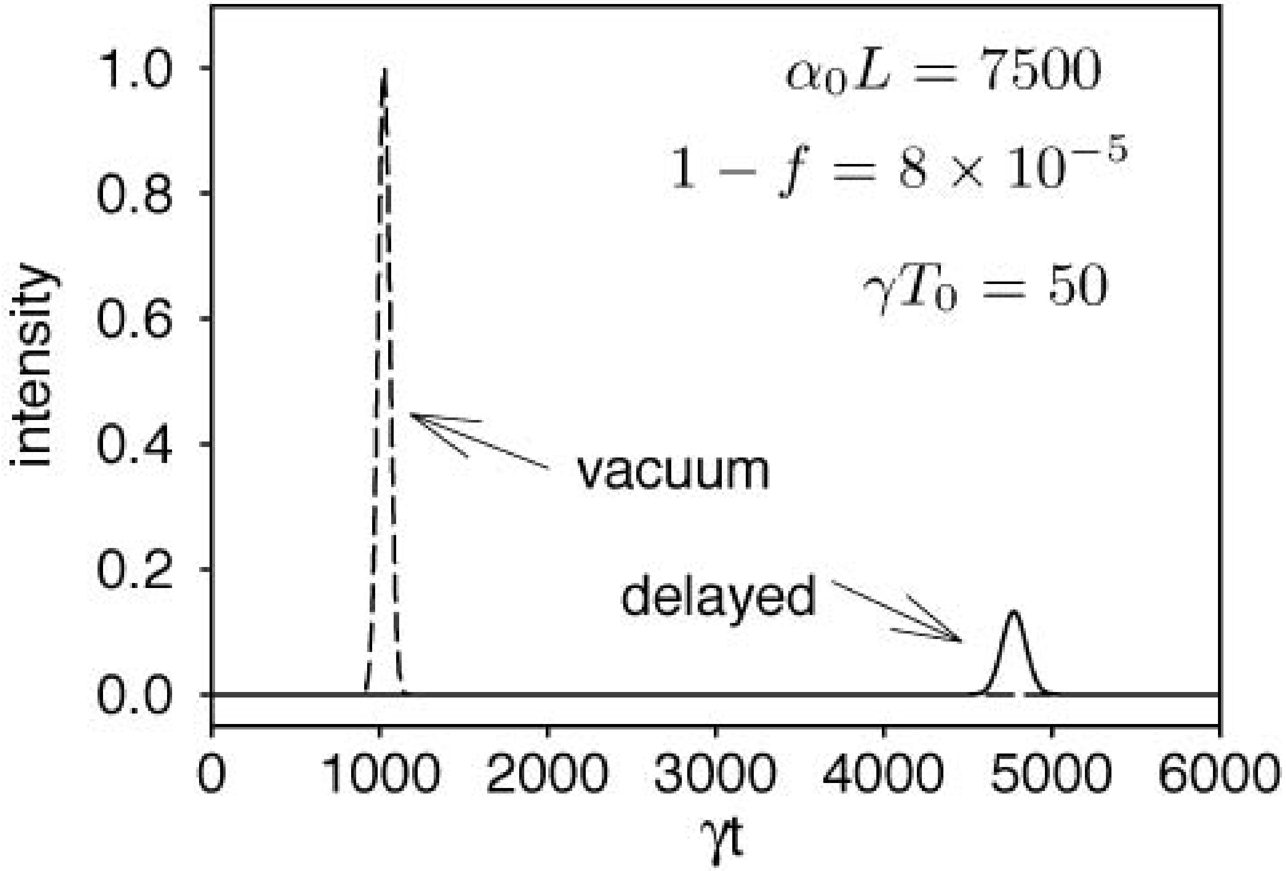
- But to achieve this time delay, one needs a large initial (before saturation) optical depth given by

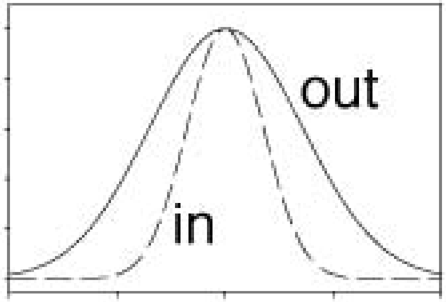
$$\alpha_0 L = (4/3)(T_{\rm del}/T_0)^2_{\rm max}.$$

- 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

$$\gamma = \frac{2}{3} B \left(\frac{T_{\rm del}}{T_0}\right)_{\rm max}$$

Numerical Example Showing Large Relative Delay





Factor-of-two pulse spreading

Relative time delay $T_{\mathrm{del}}/T_0 = 75$.

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.

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?**

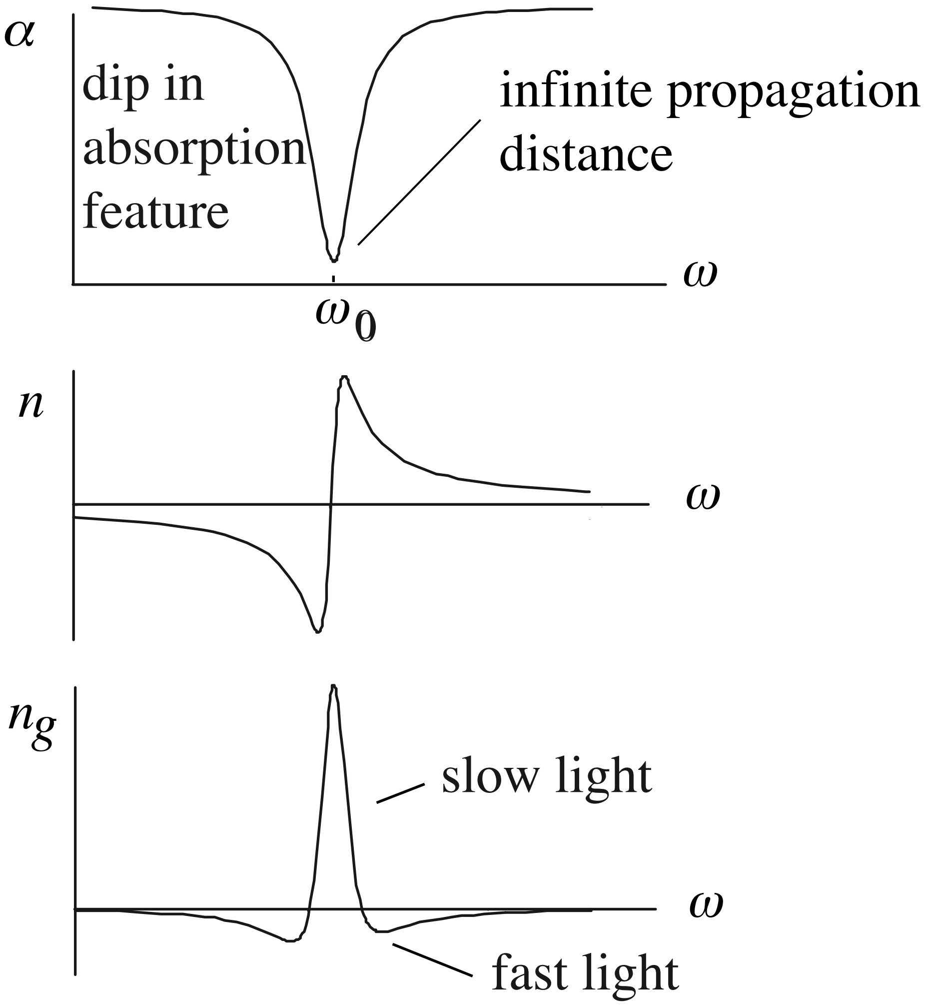
* Boyd, Gauthier, Gaeta, and Willner, PRA 2005

** 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.

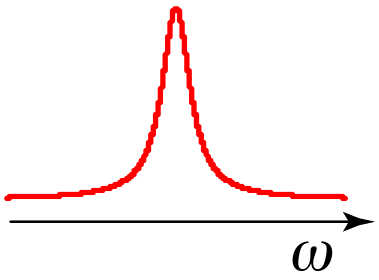
This “trick”works only for slow light.



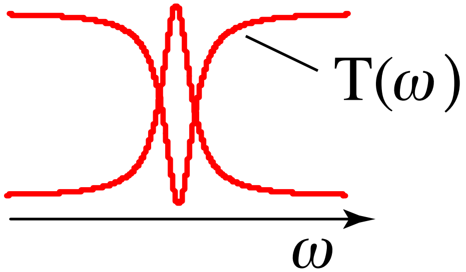
Influence of Spectral Reshaping

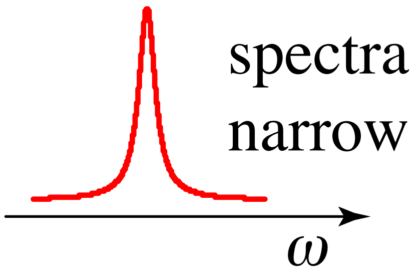
(Line-Center Operation, Dip in Gain or Absorption Feature)

input pulse



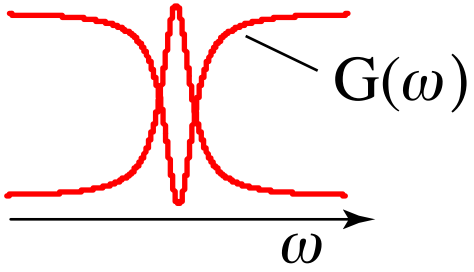
output pulse
slow-light

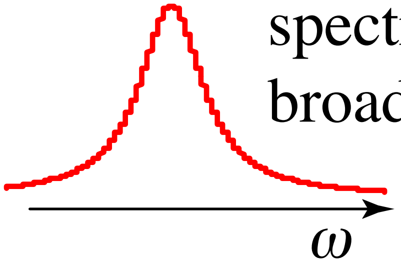




spectrally
narrowed pulse

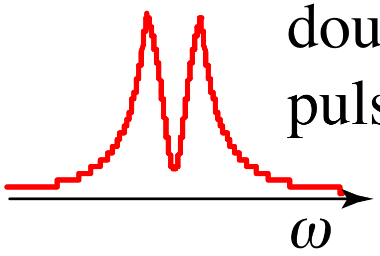
output pulse
fast-light





spectrally
broadened pulse

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



double-humped
pulse

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(32) at any frequency to avoid ASE. And we cannot have absorption larger than T = exp(-32) at the signal frequency, so signal can be measured. (Of course, the argument does not hinge on the value 32.) When examined quantitatively, these constraints impose a limit of at most several pulse-widths of delay or advancement.

$$\frac{\Delta T}{T} = \frac{1}{2}\sqrt{\alpha L}$$

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.

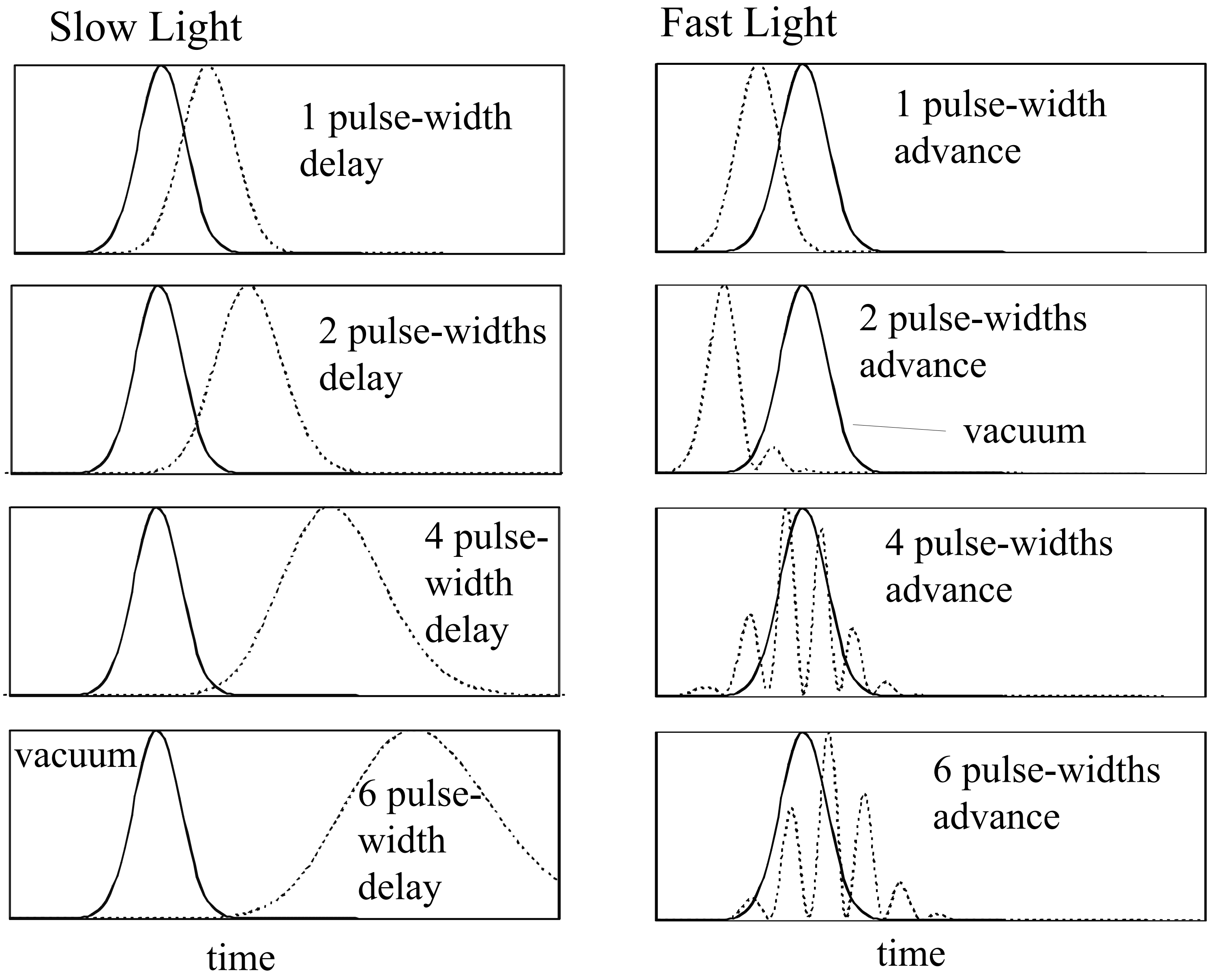
Numerical Results: Propagation through a Linear Dispersive Medium

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



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Our Approach

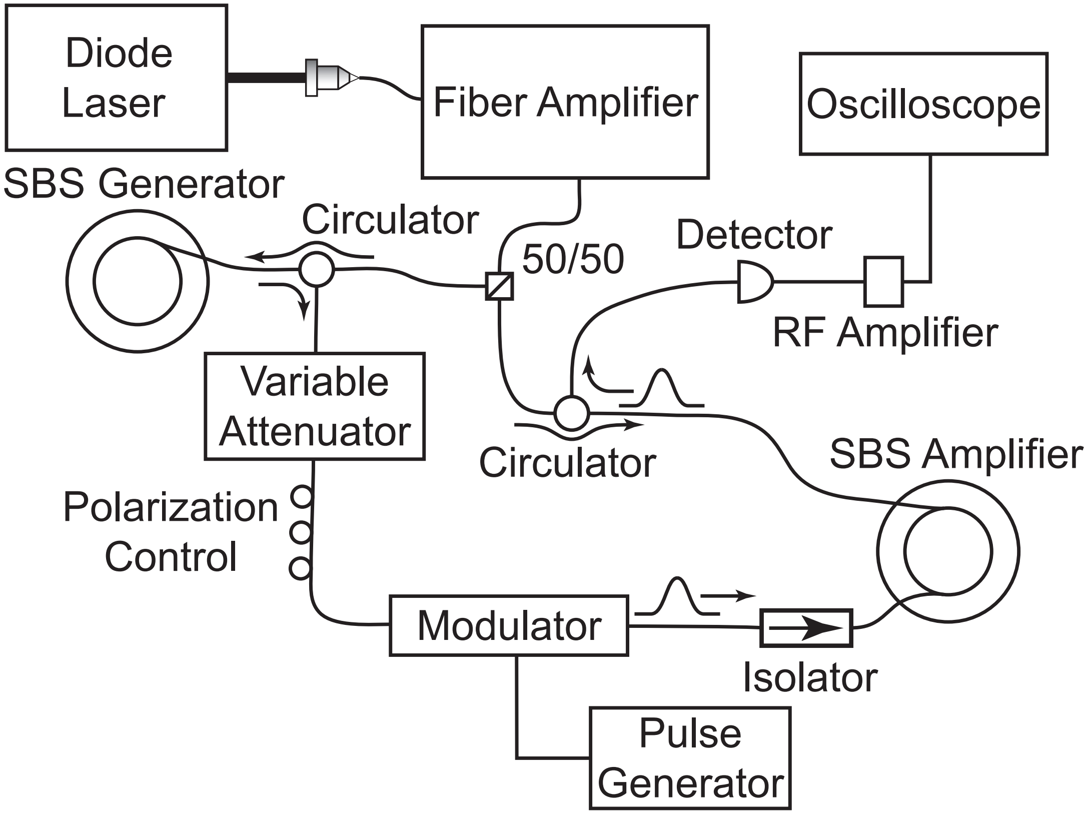
Slow light in a room-temperature solid-state material.

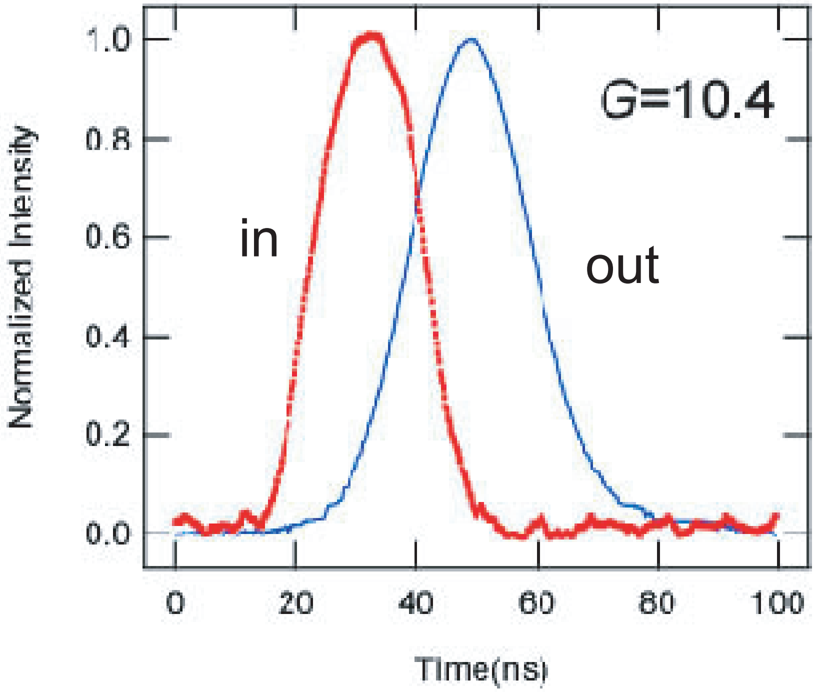
Systems under investigation:

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



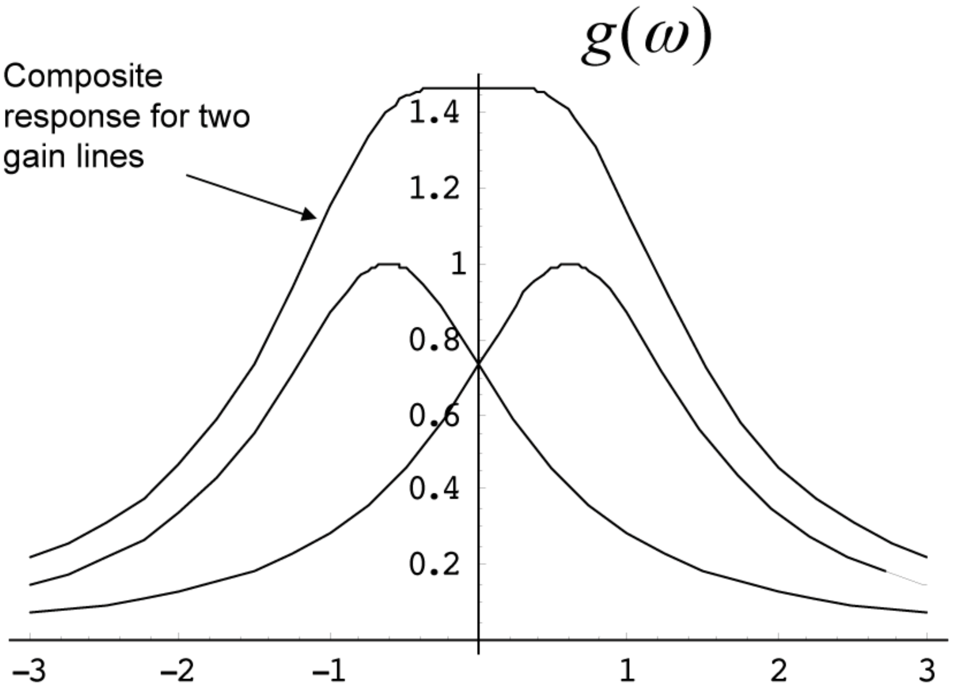


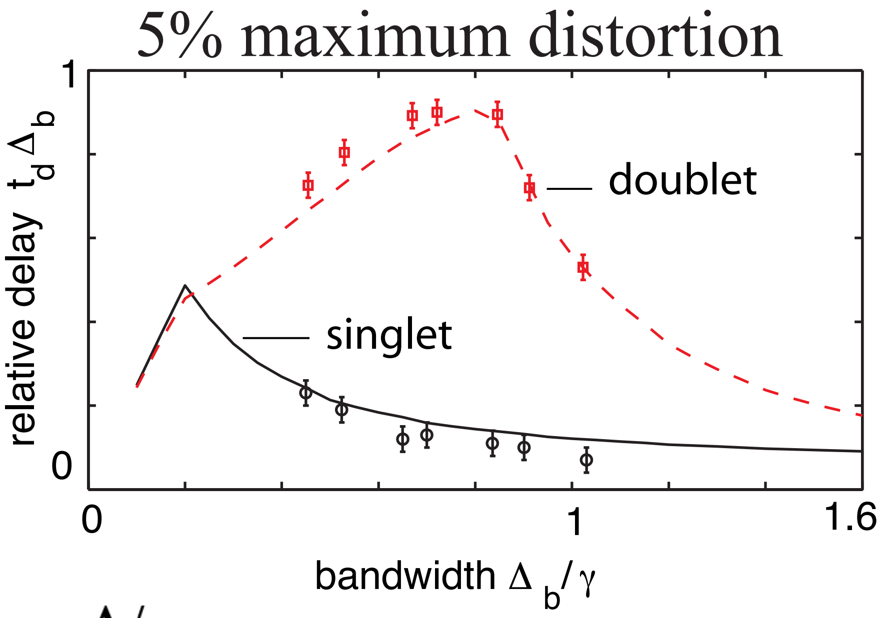
typical data

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).

Increasing the Bandwidth of a Slow Light Medium

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

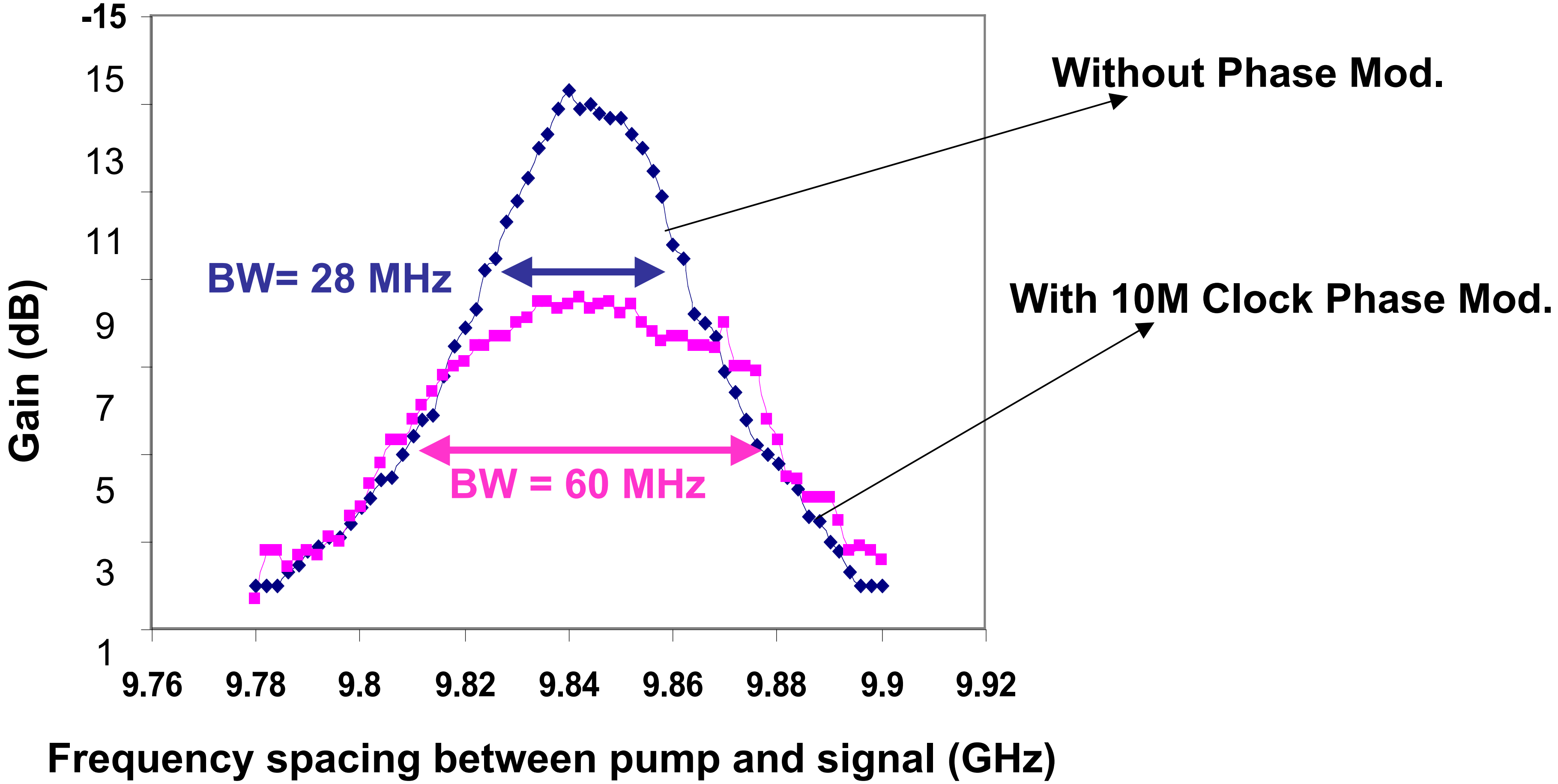




Stenner et al., Opt. Express 13 9995 (2005)

Study of SBS Gain Spectrum Broadening

Expand the BW by phase modulating the pump

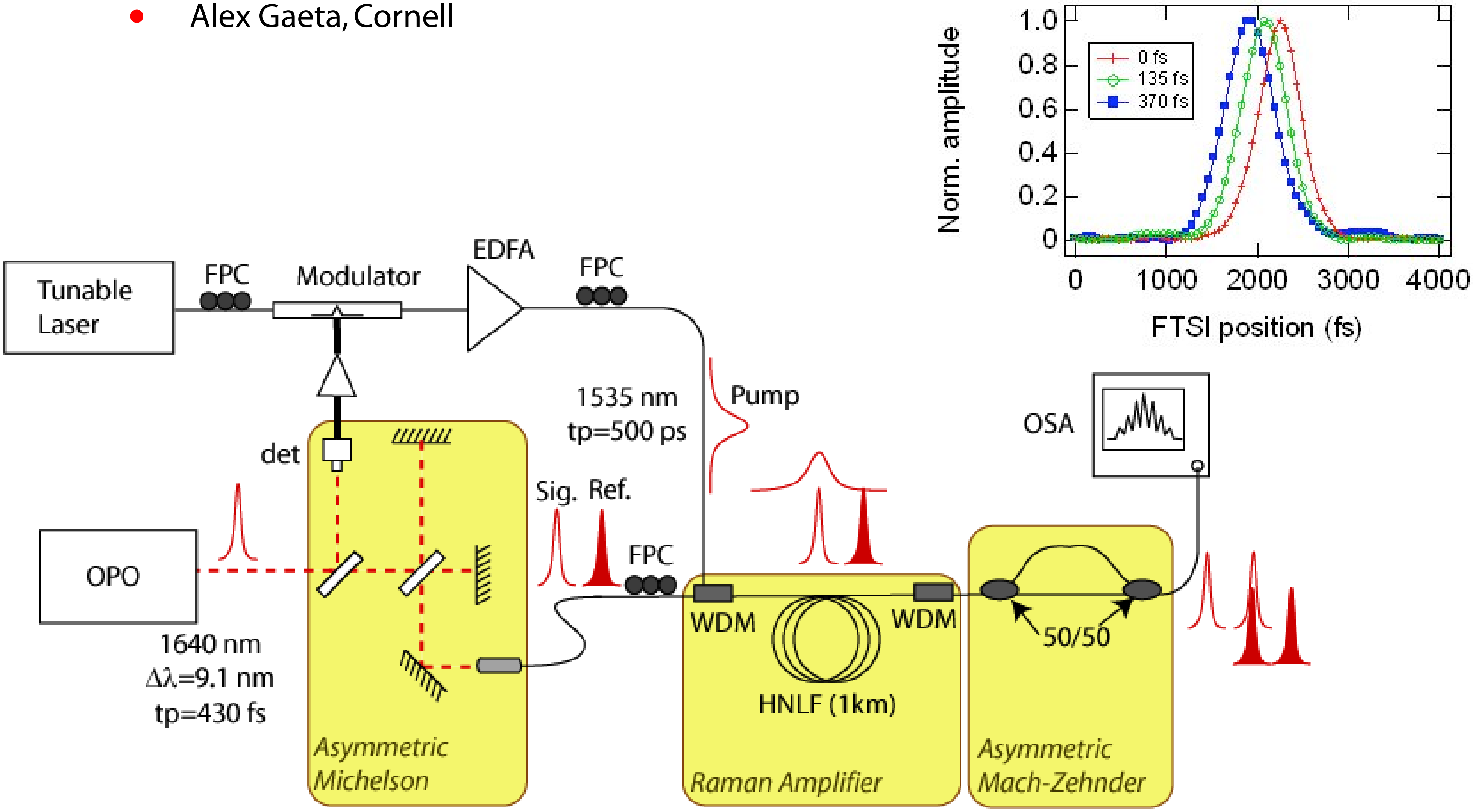


- Gain BW: 28 MHz → 60 MHz

10 MHz clock phase modulating the pump

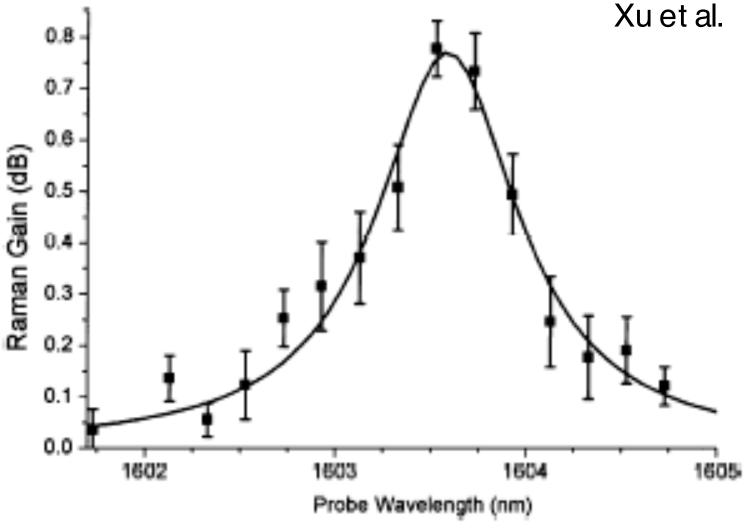
Slow-Light by Stimulated Raman Scattering

- 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

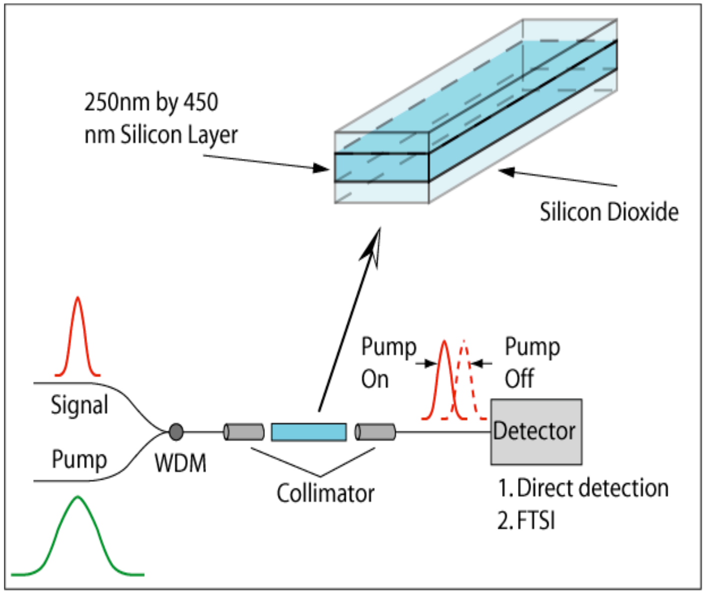


Slow Light Using SRS in a Silicon Nanostructure

- 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.

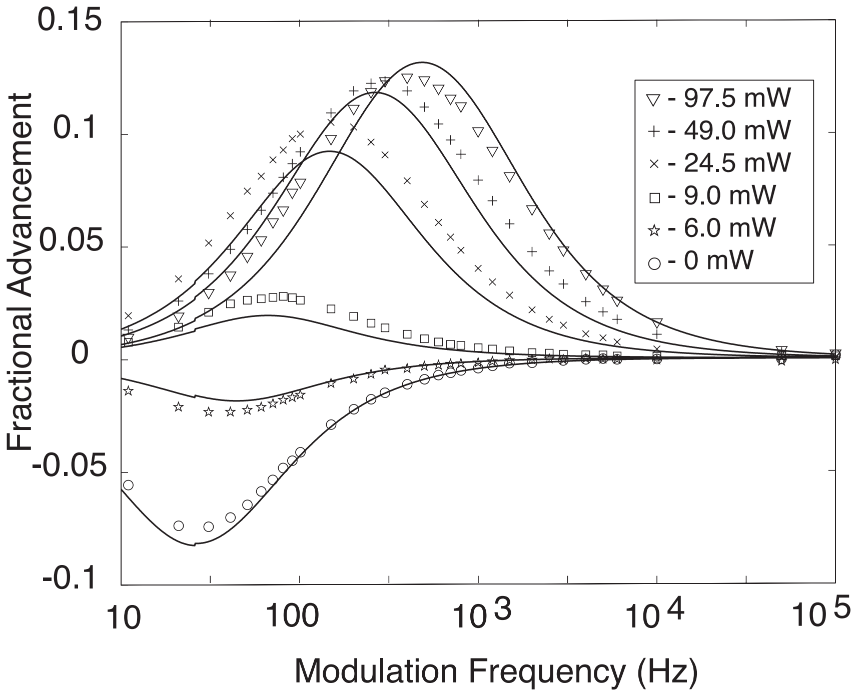


- System allows for flexibility in the operating wavelength (> 1 μm).
- Planar waveguide allows for CMOS-compatible all-optical tunable delay.

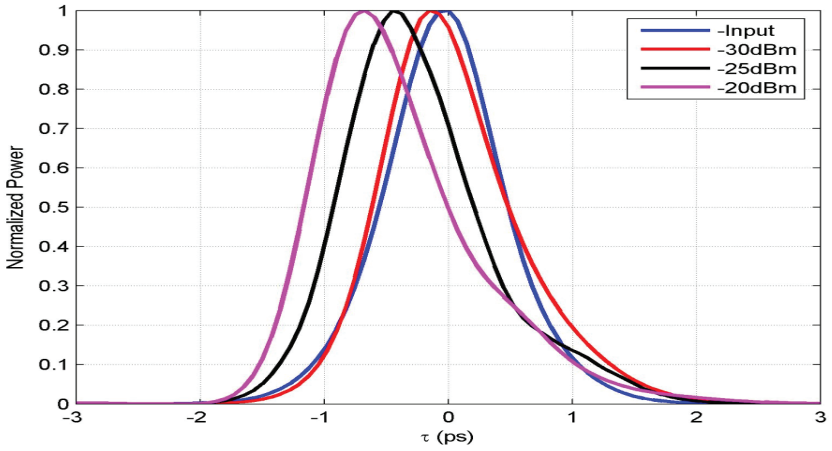
Slow Light via Coherent Population Oscillations

- 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.

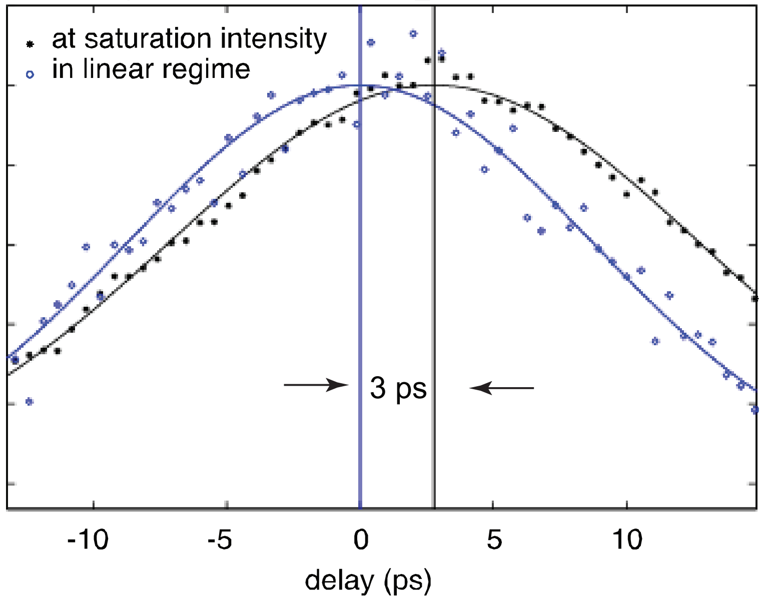
- Slow and fast light in an EDFA



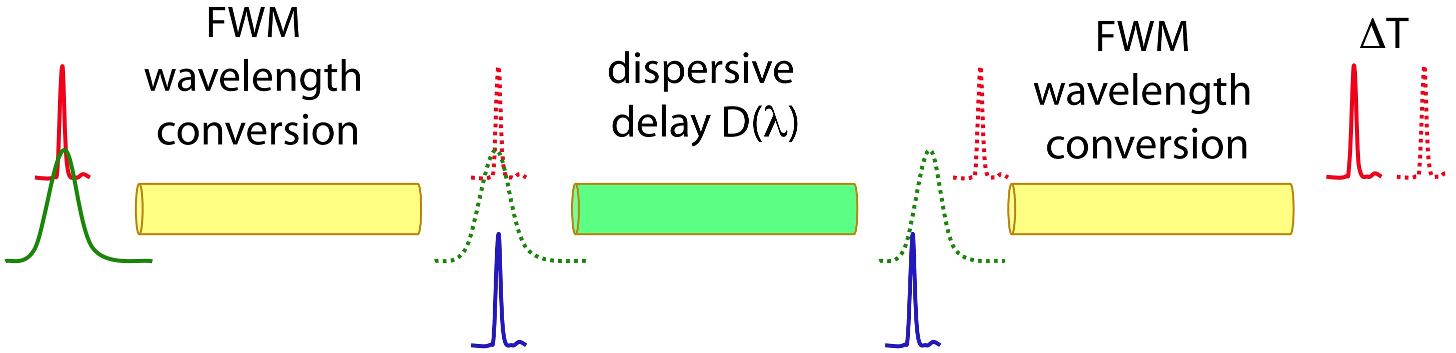
- Slow light in a SC optical amplifier



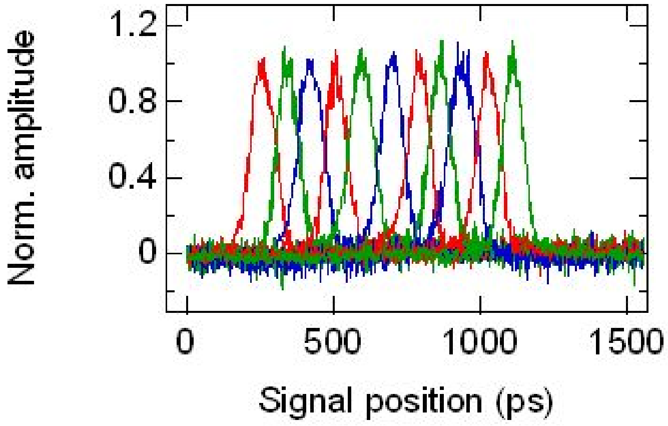
- Slow light in PbS quantum dots

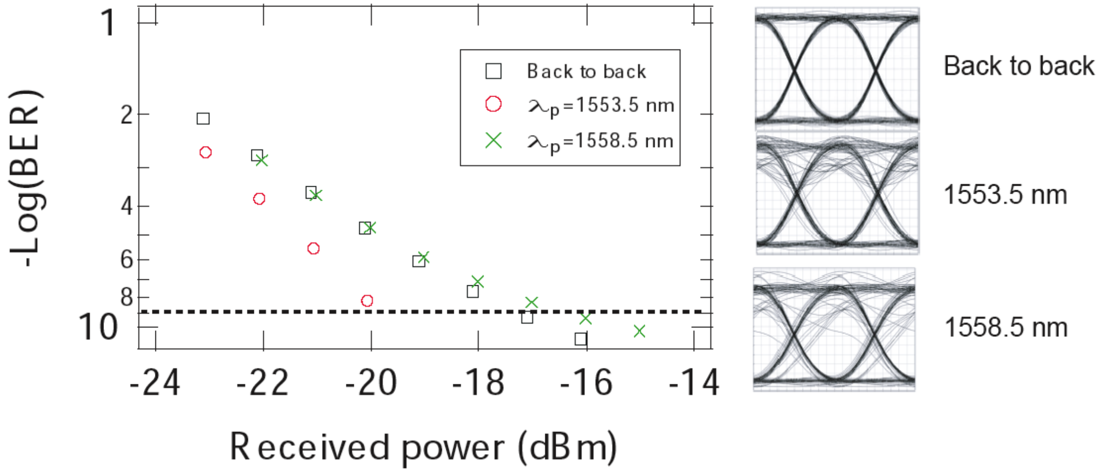


FWM-Dispersion Delay Method



- 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

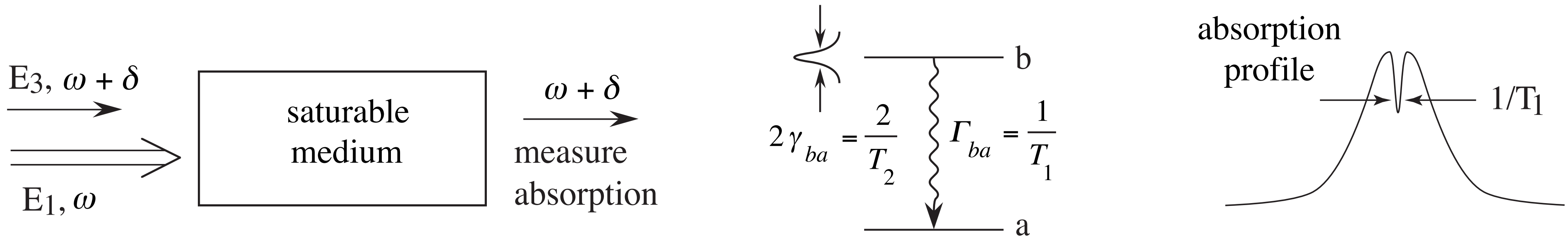




Slow Light in Optical Fibers: Applications of Slow Light in Telecom

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

Slow Light via Coherent Population Oscillations

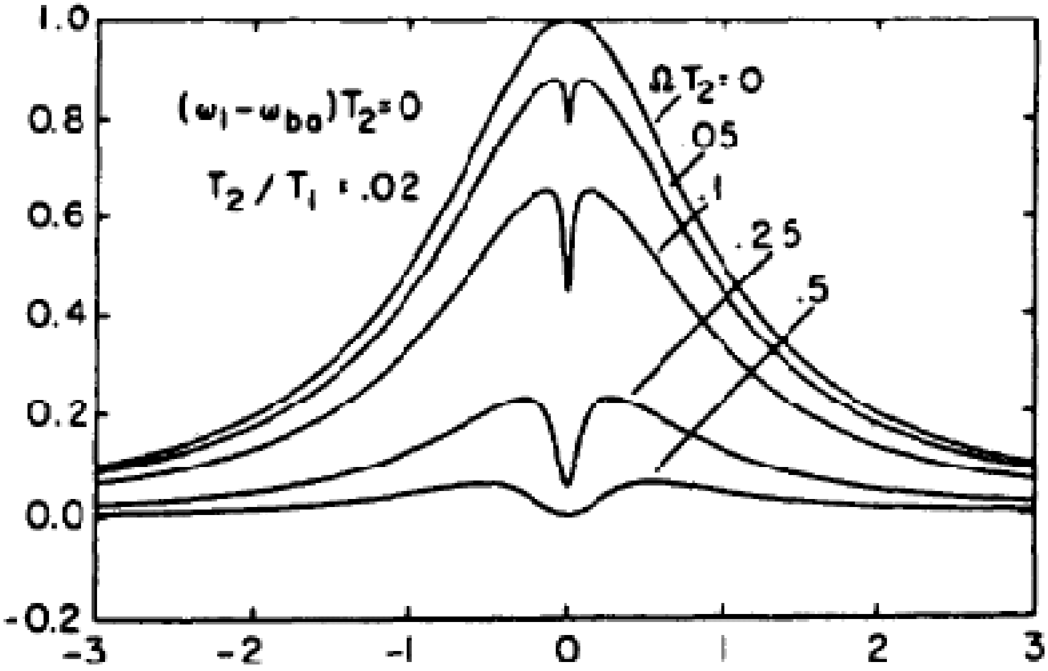


- Ground state population oscillates at beat frequency δ (for $\delta < 1/T_1$).
- Population oscillations lead to decreased probe absorption (by explicit calculation), even though broadening is homogeneous.
- Rapid spectral variation of refractive index associated with spectral hole leads to large group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

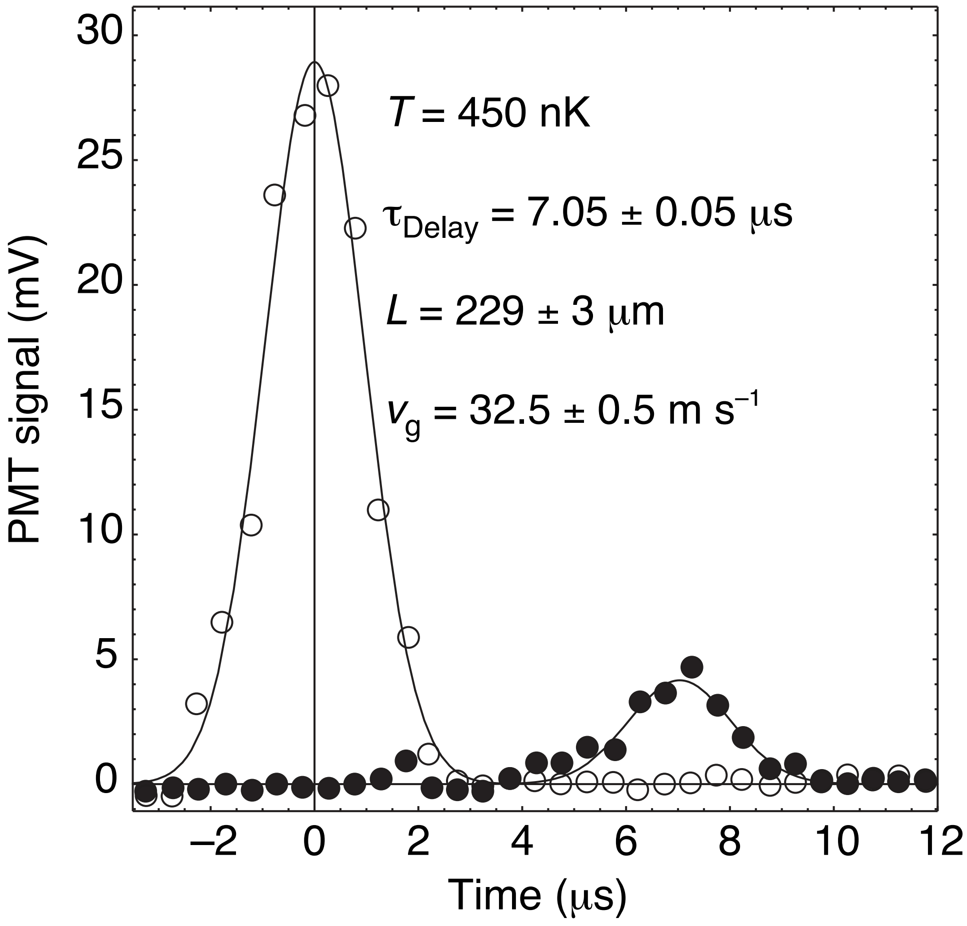
Occurs only in collisionally broadened media ($T_2 << T_1$)



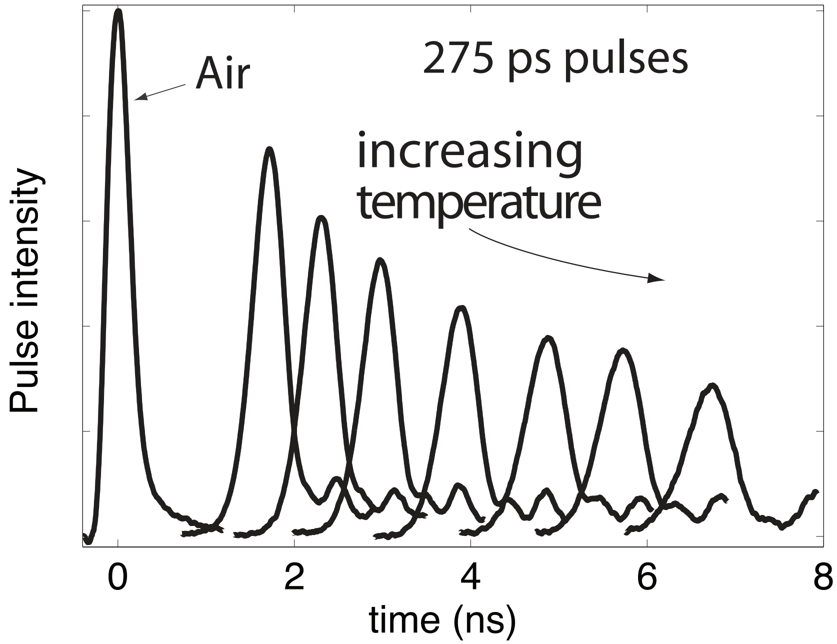
pump-probe detuning (units of $1/T_2$)

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

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!

And thanks to NSF and DARPA for financial support!

Our results are posted on the web at:

http://www.optics.rochester.edu/~boyd

Physics is all about asking the right questions

Just ask

Evelyn **Hu**

Watt Webb (or James **Watt**)

Michael **Ware**

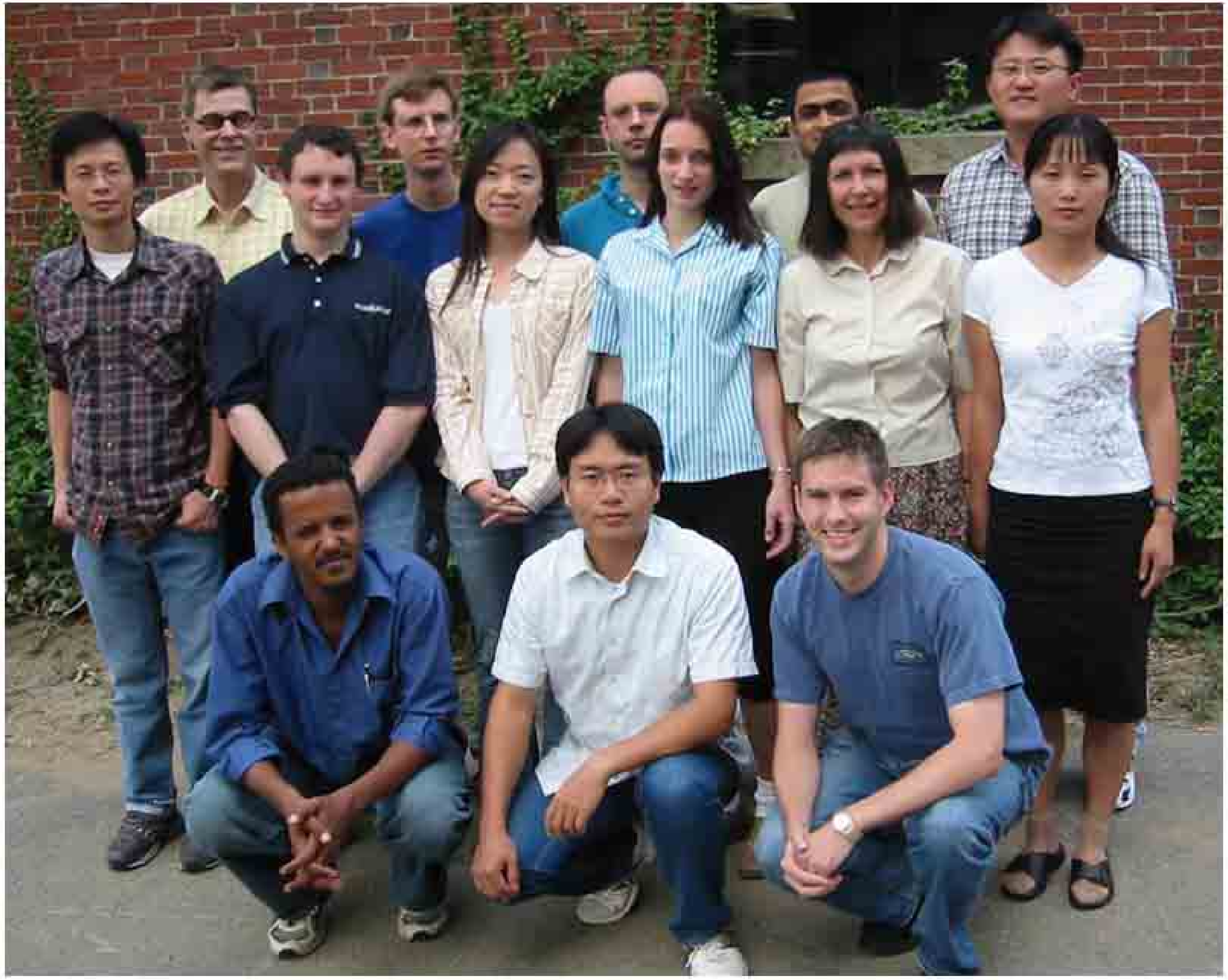
Wen I Wang

Kam **Wai** Chan

Not to mention

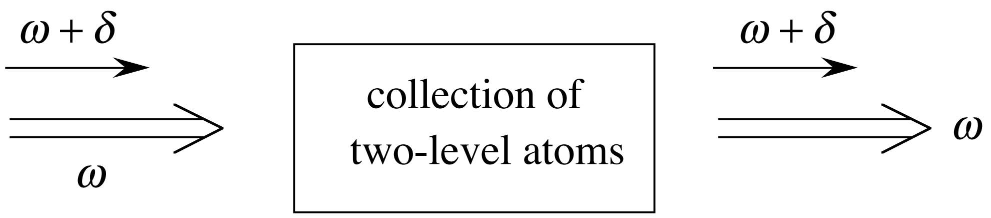
Lene **Hau**

Special Thanks to My Students and Research Associates

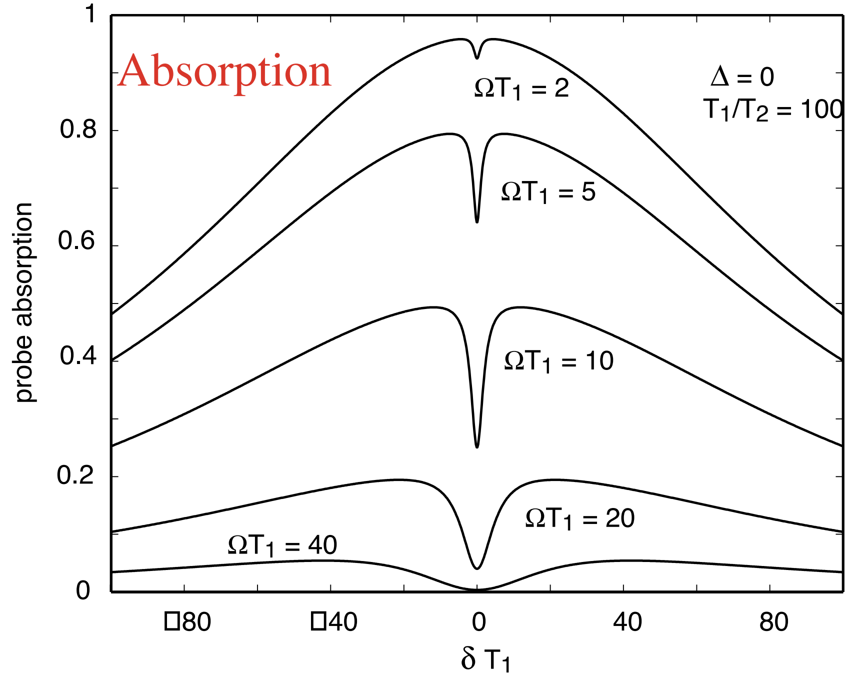


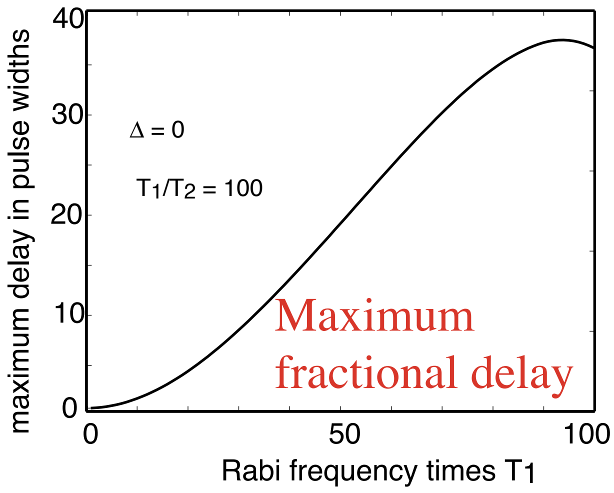
Thank you for your attention!

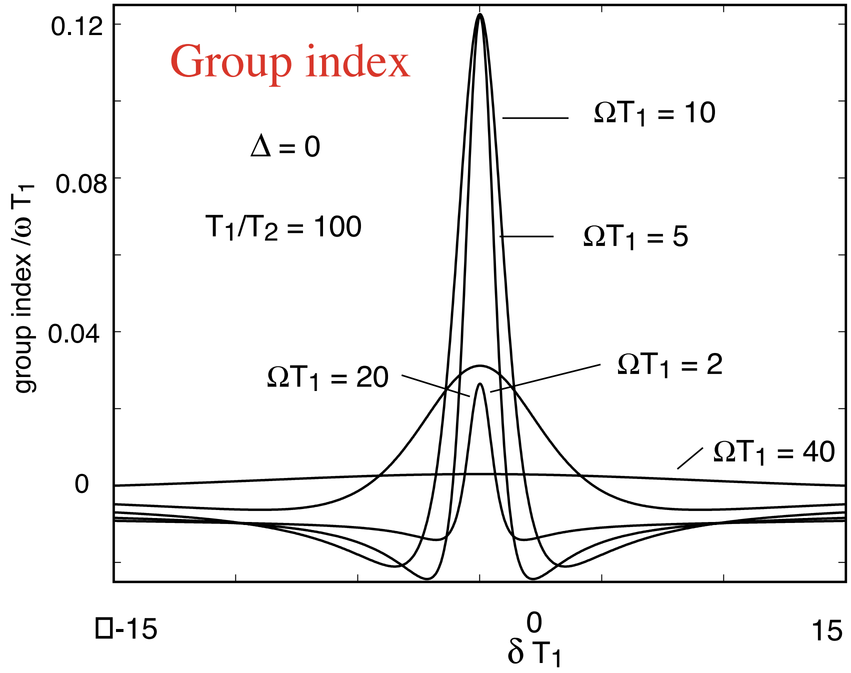
Prospects for Large Fractional Delays Using CPO



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







Boyd et al., Laser Physics 2005.