Progress in Slow Light and Quantum Imaging

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with Aaron Schweinsberg, Hye Jeong Chang, Colin O’Sullivan-Hale
Petros Zerom, Giovanni Piredda, Zhimin Shi, Heedeuk Shin, and others.

Presented at Columbia University, December 5, 2005.

Interest in Slow Light

Intrigue: Can (group) refractive index really be 10^6?

Fundamentals of optical physics

Optical delay lines, optical storage, optical memories

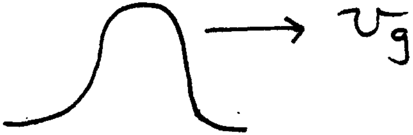
Implications for quantum information

And what about fast light ($v > c$ or negative)?

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

Group Velocity

Pulse
(wave packet)



Group velocity given by $v_g = \frac{d\omega}{dk}$

For $k = \frac{n\omega}{c}$. $\frac{dk}{d\omega} = \frac{1}{c}\left(n + \omega \frac{dn}{d\omega}\right)$

Thus

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

Thus $n_g \neq n$ in a dispersive medium!

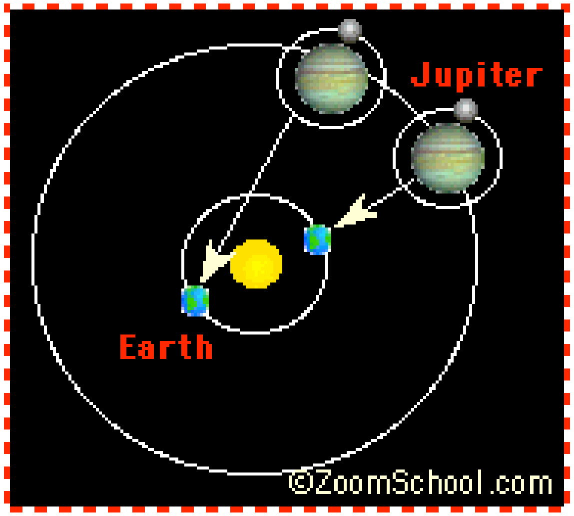
Switch to Overheads

Determination of the Velocity of Light*

"Astronomical" Methods

Römer (1676) First evidence that velocity of light is finite!

Observed an apparent variation of up to 22 minutes in the orbital period of the satellite Io in its orbit about Jupiter.



Deduced that c = 225,000 km/sec

(Actually, light transit time from sun to earth is just over 8 minutes, and c = 299,793 km/sec)

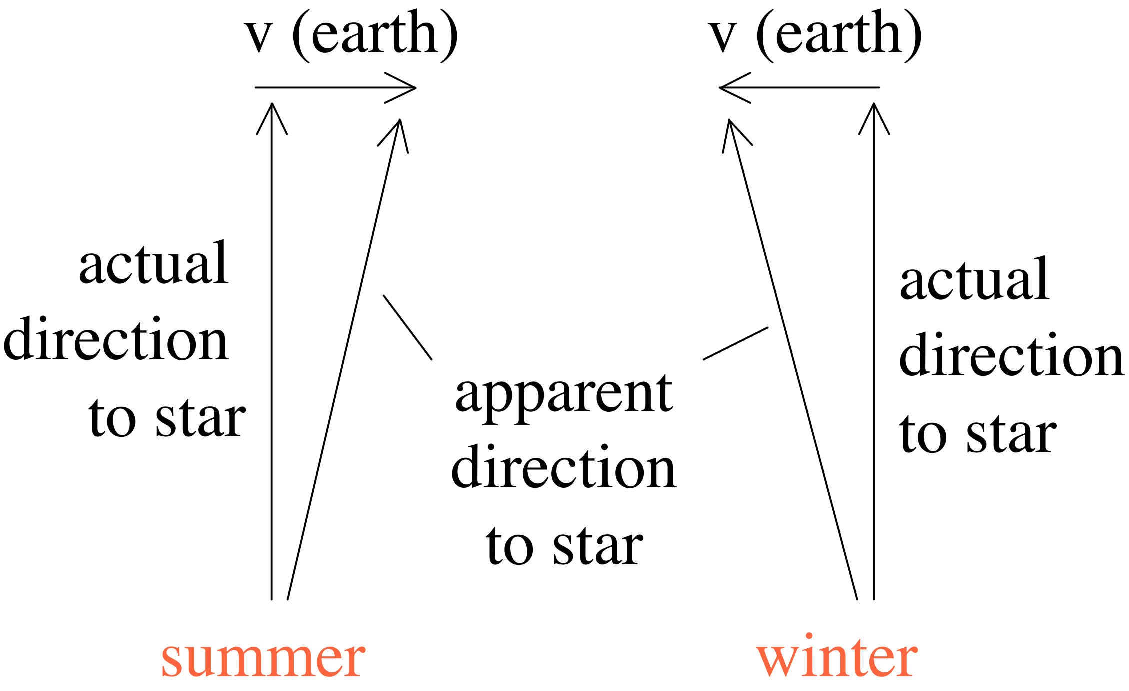
*See, for instance, Jenkins and White, 1976.

Determination of the Velocity of Light

Astronomical Methods

Bradley (1727); Aberration of star light.

Confirmation of the finite velocity of light.



v (earth)

v (earth)

actual direction to star

apparent direction to star

actual direction to star

summer

winter

$$v(\text{earth}) \approx 30 \text{ km/s}$$

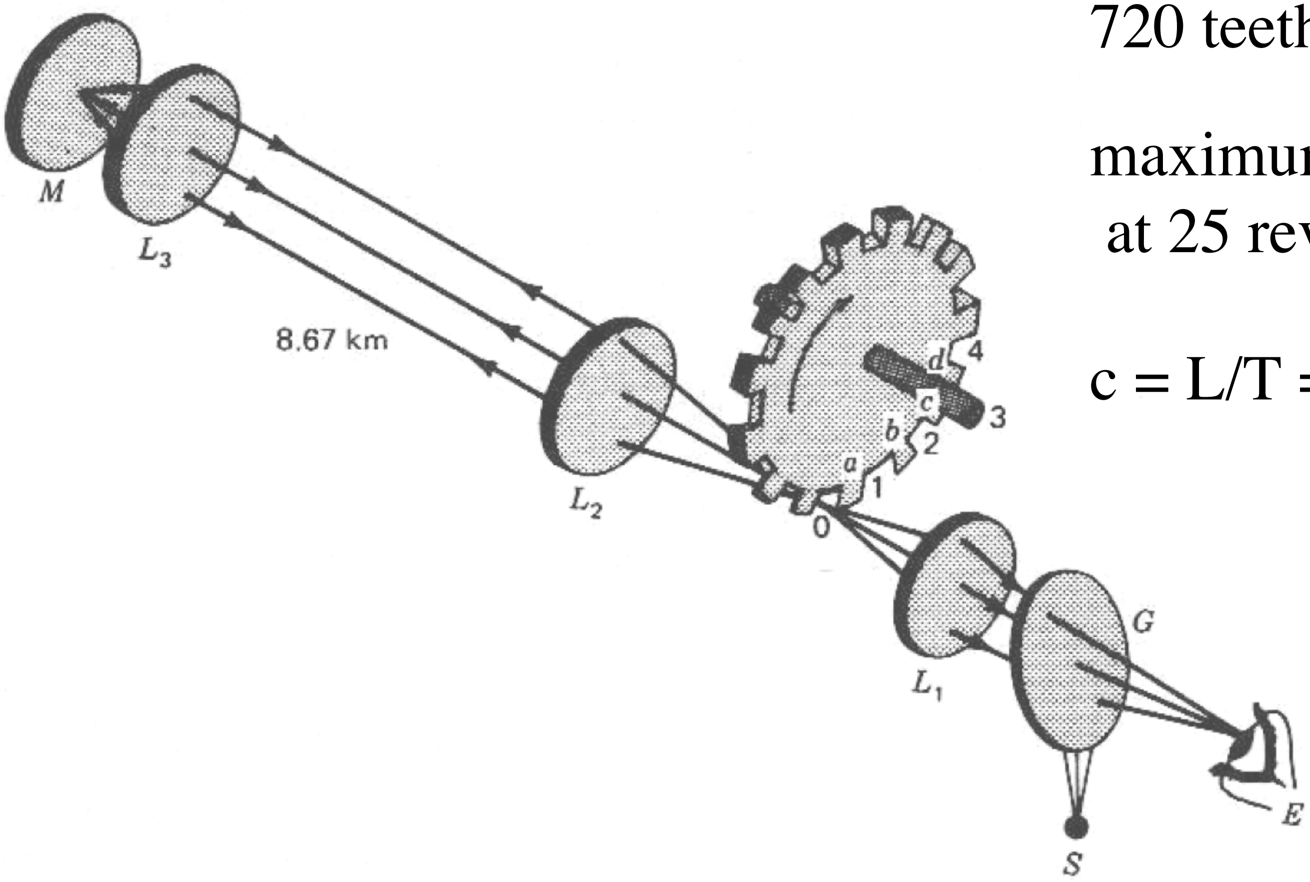
$$\tan\alpha = \frac{v(\text{earth})}{c}$$

$$\alpha = 20.5 \text{ arcsec}$$

Determination of the Velocity of Light

Laboratory Methods

Fizeau (1849) Time-of-flight method



720 teeth in wheel

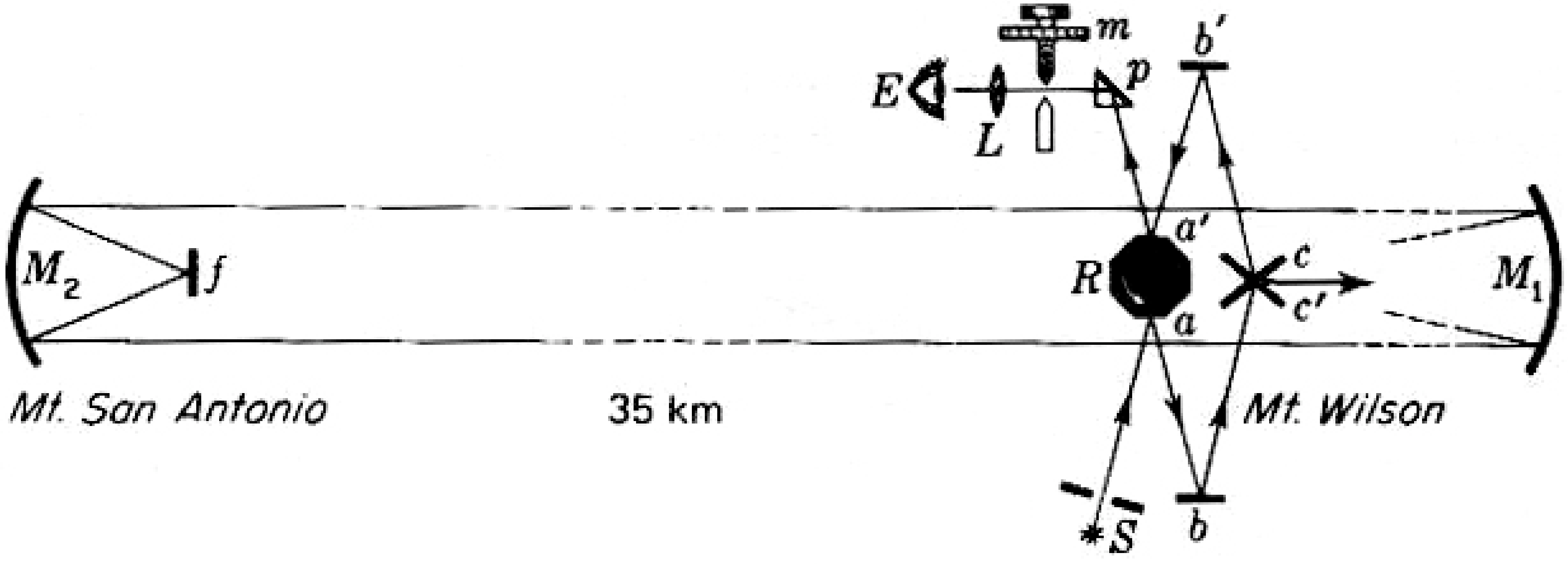
maximum transmission
at 25 revolutions/sec

c = L/T = 320,000 km/s

Determination of the Velocity of Light

Laboratory Methods

Michelson (1926); Improved time of flight method.



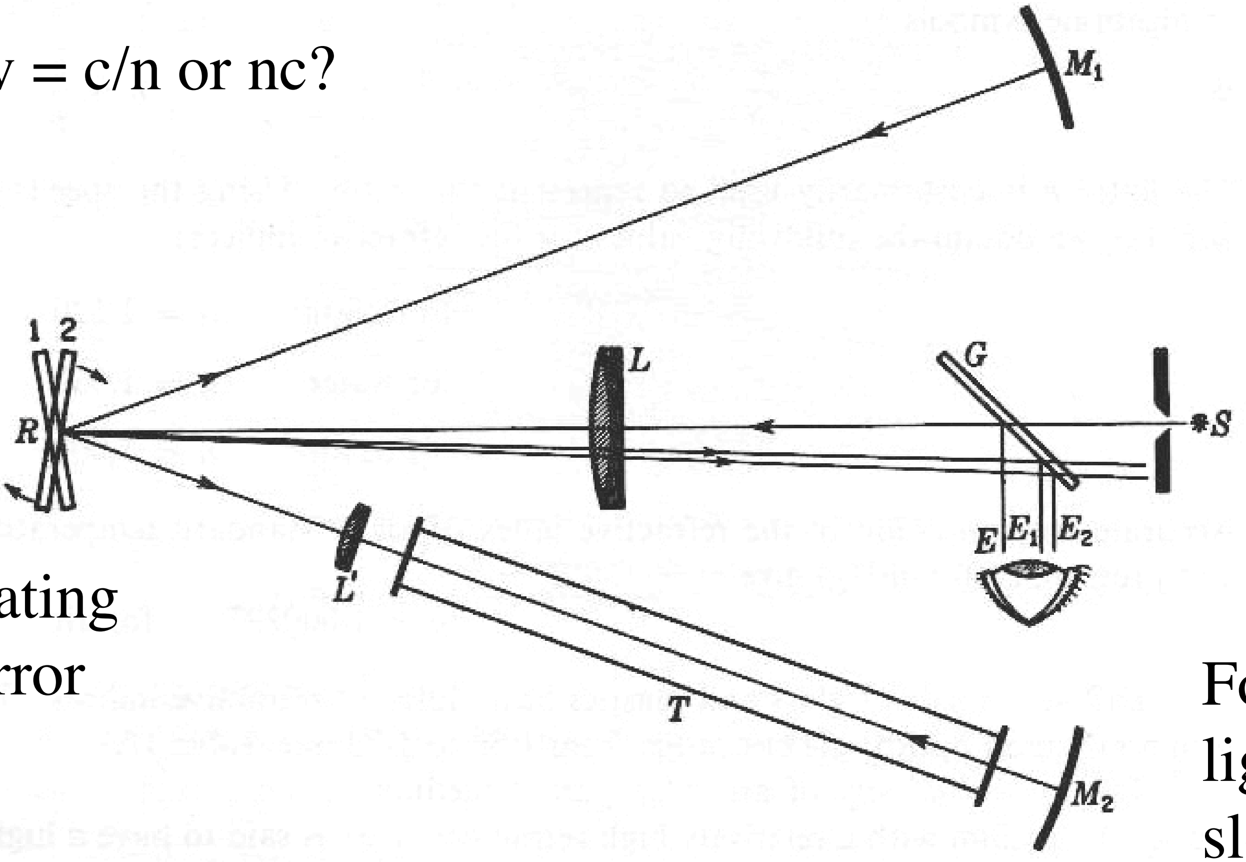
Rotating octagonal mirror

c = 299,296 km/s (or 299,298 km/s)

Velocity of Light in Matter

Foucault (1850) Velocity of light in water.

Is v = c/n or nc?



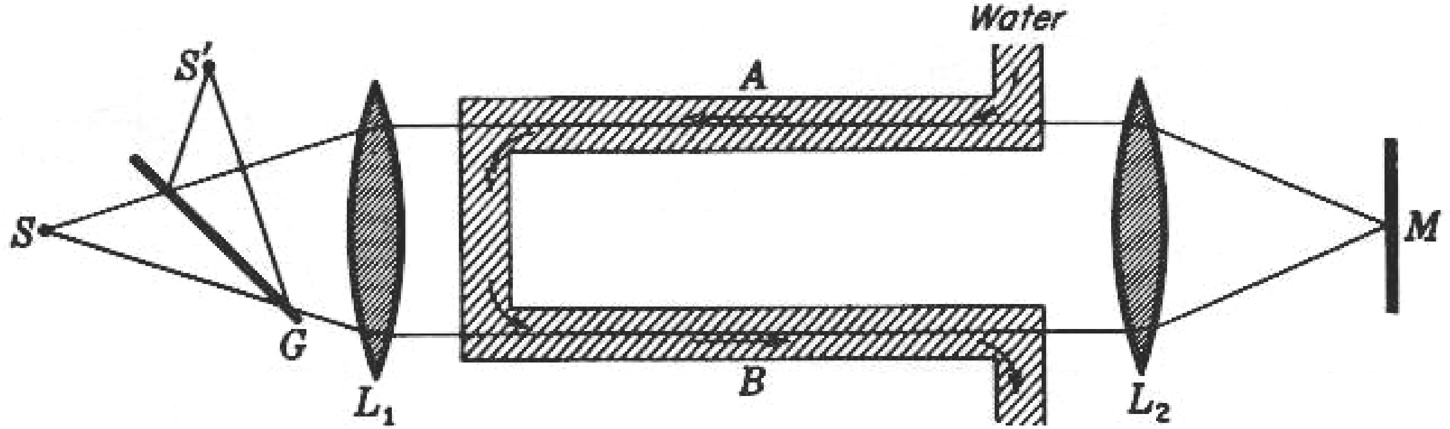
rotating
mirror

Foucault finds that
light travels more
slowly in water!

Velocity of Light in Moving Matter

Fizeau (1859); Velocity of light in flowing water.

V = 700 cm/sec; L = 150 cm; displacement of 0.5 fringe.



Modern theory: relativistic addition of velocities

$$\mathrm{v} = \frac{\mathrm{c}/n + V}{1 + (V/\mathrm{c})(1/n)} \approx \frac{c}{n} + V\left(1 - \frac{1}{n^2}\right)$$

Fresnel "drag" coefficient

Approaches to Slow Light Propagation

- Use of quantum coherence (to modify the spectral dependence of the atomic response)

  e.g., electromagnetically induced transparency

- Use of artificial materials (to modify the optical properties at the macroscopic level)

  e.g., photonic crystals (strong spectral variation of refractive index occurs near edge of photonic bandgap)

- Want v_g very different from v_p

  Need very large dispersion

  Study resonances of atomic vapor

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

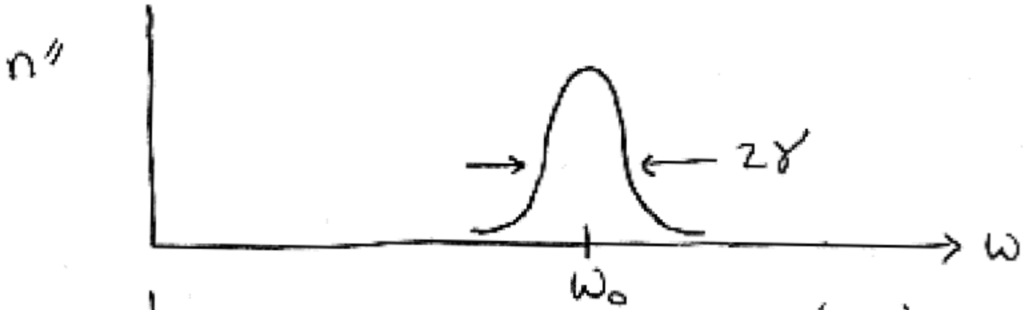
Light Propagation in Atomic Vapors

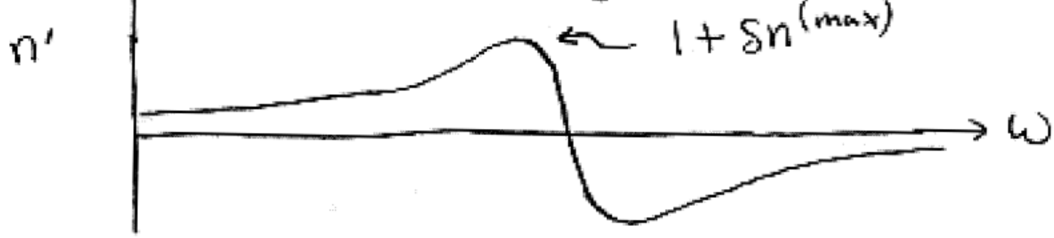
$$n = \sqrt{\varepsilon} = \sqrt{1+4\pi\chi} \qquad \chi = \frac{Ne^2/2m\omega_0}{(\omega_0-\omega) - i\gamma}$$

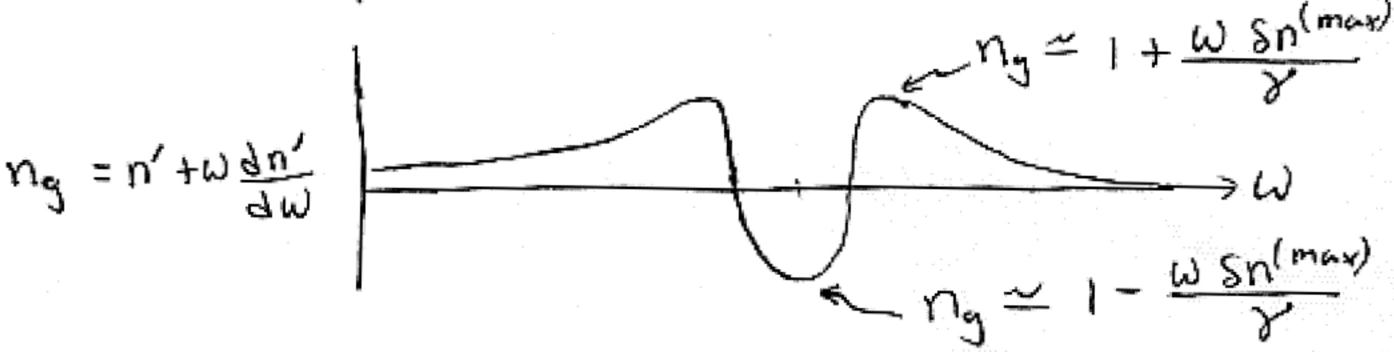
For N not too large $\quad n = n' + in'' \simeq 1 + 2\pi\chi$

$$n' \simeq 1 + \frac{\pi N e^2}{m\omega_0}\,\frac{\omega_0-\omega}{(\omega_0-\omega)^2+\gamma^2}$$

$$n'' = \frac{\pi N e^2}{2m\omega_0\gamma}\,\frac{\gamma^2}{(\omega_0-\omega)^2+\gamma^2}$$







$$\frac{\omega\,\delta n^{(max)}}{\gamma} \simeq \frac{2\pi(5\times10^{14})(0.1)}{2\pi\,(1\times10^{9})} = 5\times10^{4} \sim (!)$$

n_g can range from $+5\times10^4$ to -5×10^4.

(But with lots of absorption)

How to Produce Slow Light ?

Group index can be as large as

$$n_g \simeq 1 + \frac{\omega\, \delta n^{(max)}}{\gamma}$$

Use nonlinear optics to

(1) decrease line width γ
(produce sub-Doppler linewidth)

(2) decrease absorption
(so transmitted pulse is detectable)

Slow Light in Atomic Vapors

Slow light propagation in atomic vapors, facilitated by quantum coherence effects, has been successfully observed by

Hau and Harris

Welch and Scully

Budker

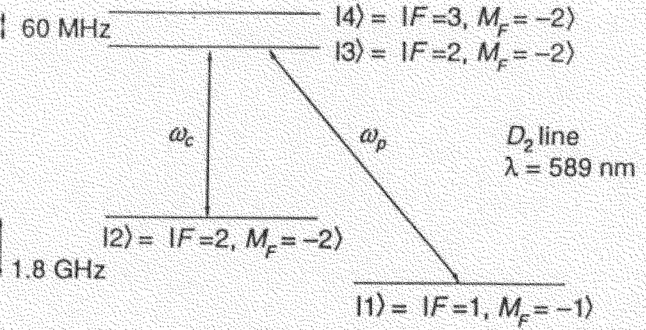
and others

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

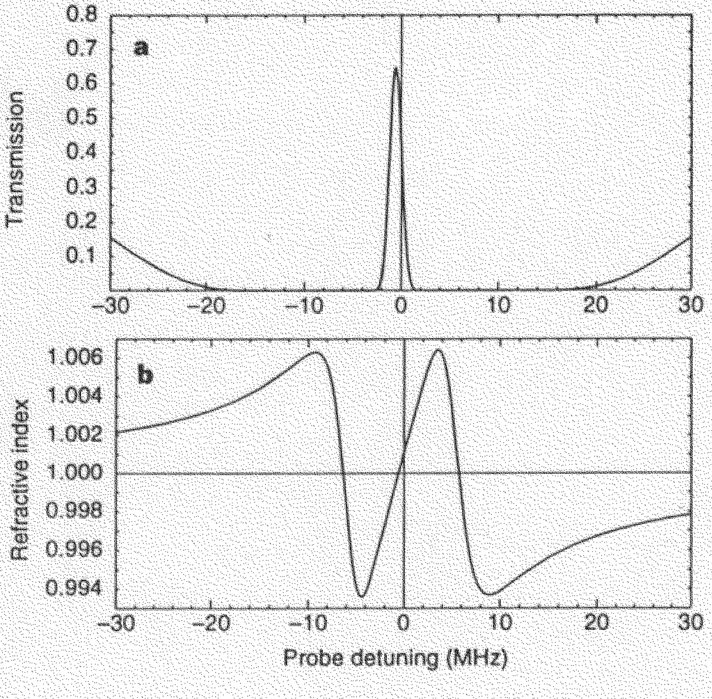
Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§

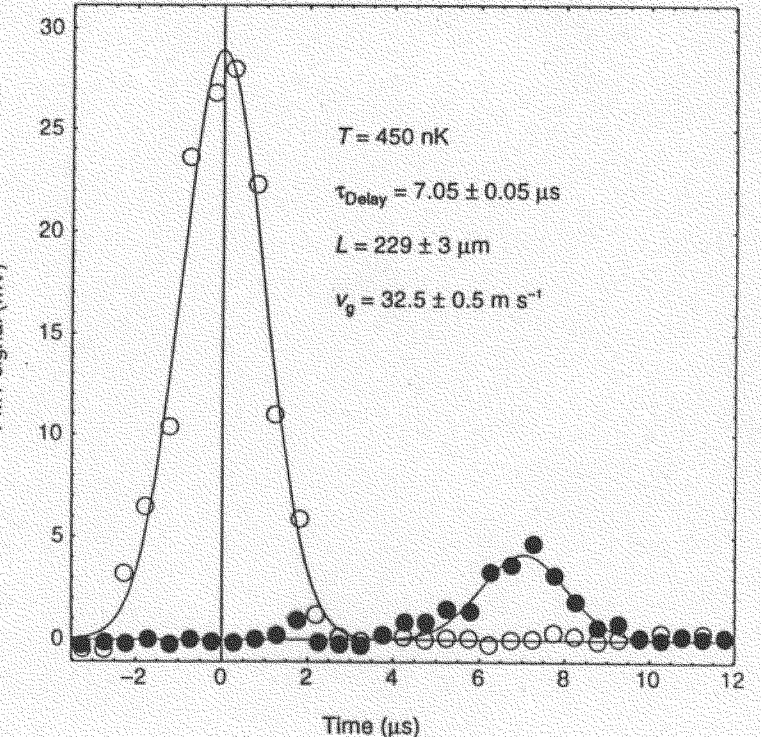
* *Rowland Institute for Science, 100 Edwin H. Land Boulevard, Cambridge, Massachusetts 02142, USA*
† *Department of Physics, § Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*
‡ *Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*

Nature, 397, 594, (1999).

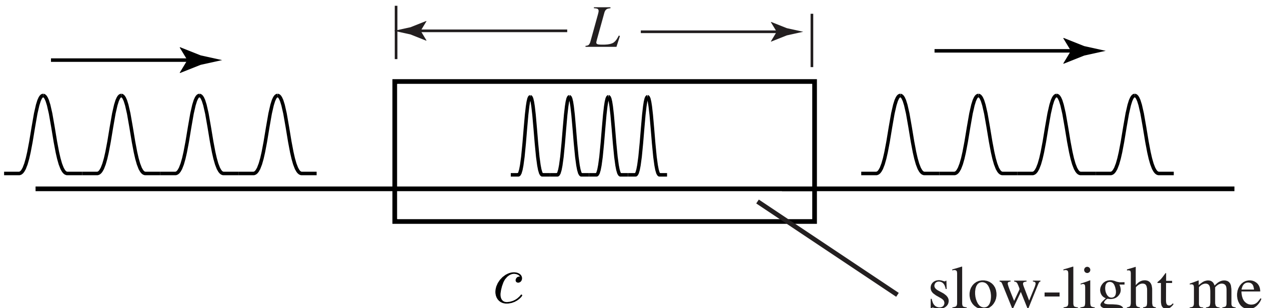


$$v_g = \frac{c}{n(\omega_p) + \omega_p \frac{dn}{d\omega_p}} \approx \frac{\hbar c \epsilon_0}{2\omega_p} \frac{|\Omega_c|^2}{|\mu_{13}|^2 N}$$





Review of Slow-Light Fundamentals



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

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

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

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

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 $\approx 10^3$ bits

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

Modeling of Maximum Delay of Slow-Light Systems

Our model [1] includes gvd and spectral reshaping of pulses.

We conclude that there are no *fundamental* limitations
to the maximum fractional pulse delay.

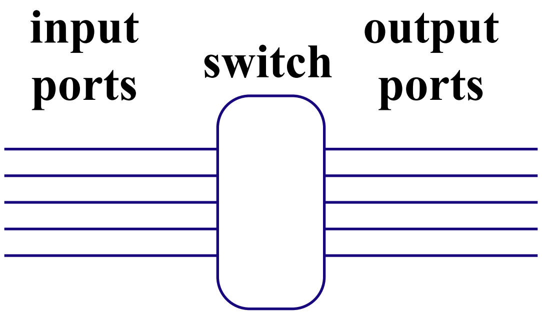
However, there are serious *practical* limitations,
primarily associated with residual absorption.

Strategy: pump harder to saturate more fully to reduce
residual absorption.

[1] Boyd, Gauthier, Gaeta, and Willner, Phys. Rev. A 71, 023801, 2005.

Slow Light and Optical Buffers

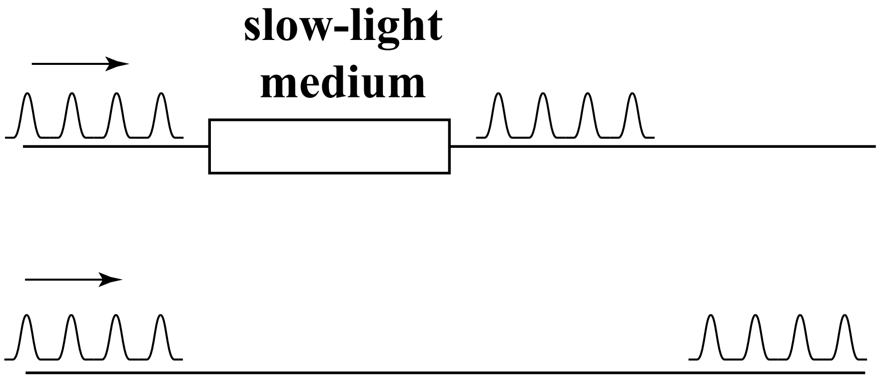
All-Optical Switch


input ports

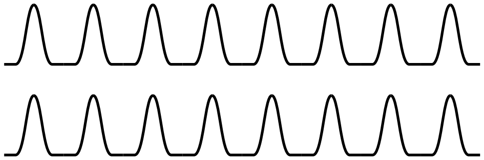
switch

output ports

Use Optical Buffering to Resolve Data-Packet Contention


slow-light medium

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

Challenge/Goal

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

Solution: Slow light enabled by coherent population oscillations (a quantum coherence effect that is relatively insensitive to dephasing processes).

Slow Light in Ruby

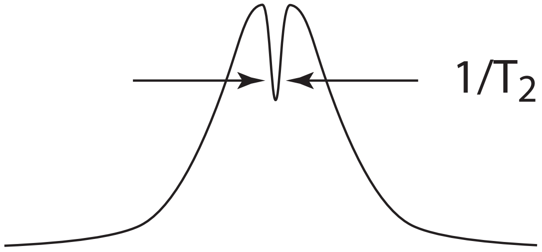
Recall that $n_g = n + \omega(dn/d\omega)$. Need a large $dn/d\omega$. (How?)

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

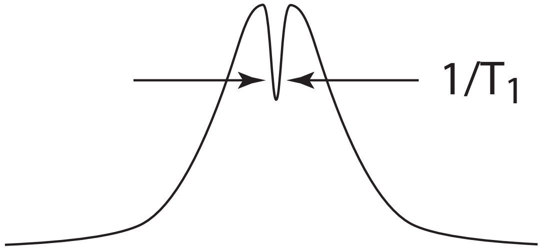
Well-known “trick” for doing so:

Make use of spectral holes due to population oscillations.

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



inhomogeneously
broadened medium

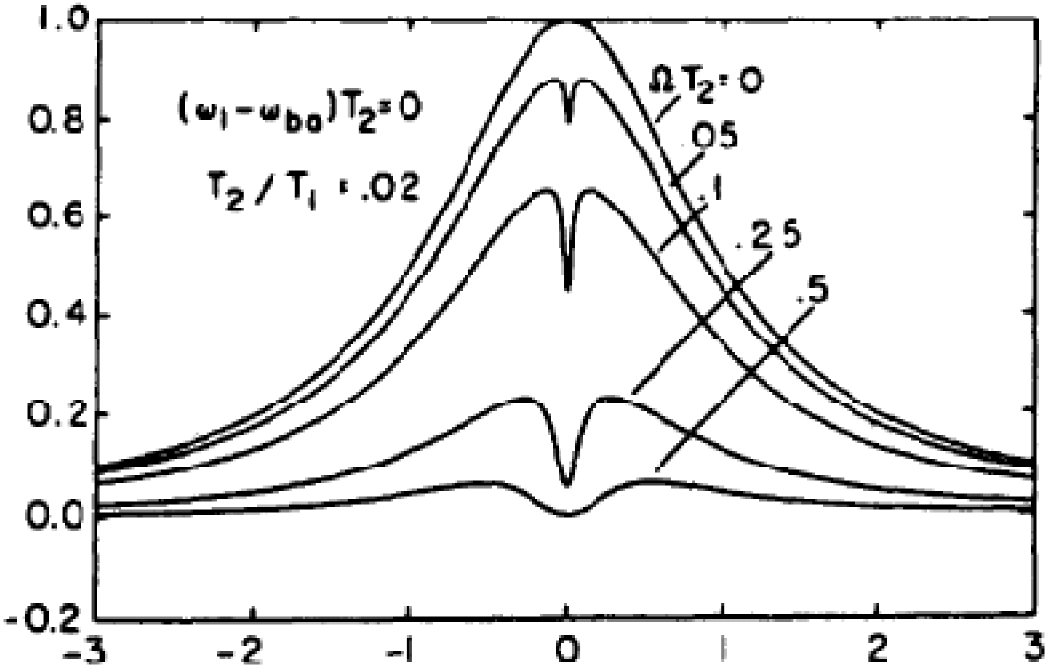


homogeneously
broadened medium
(or inhomogeneously
broadened)

PRL 90,113903(2003).

Spectral Holes in Homogeneously Broadened Materials

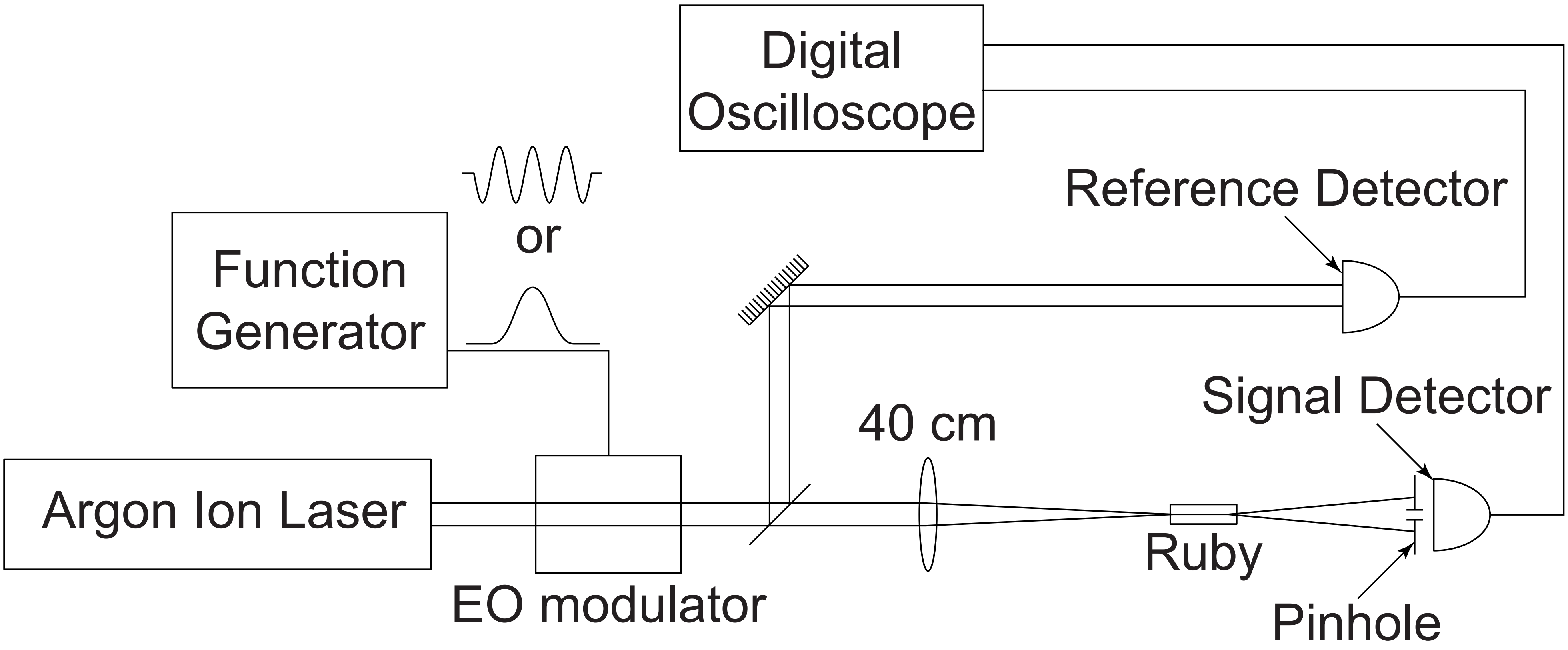
Occurs only in collisionally broadened media ($T_2 << T_1$)



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

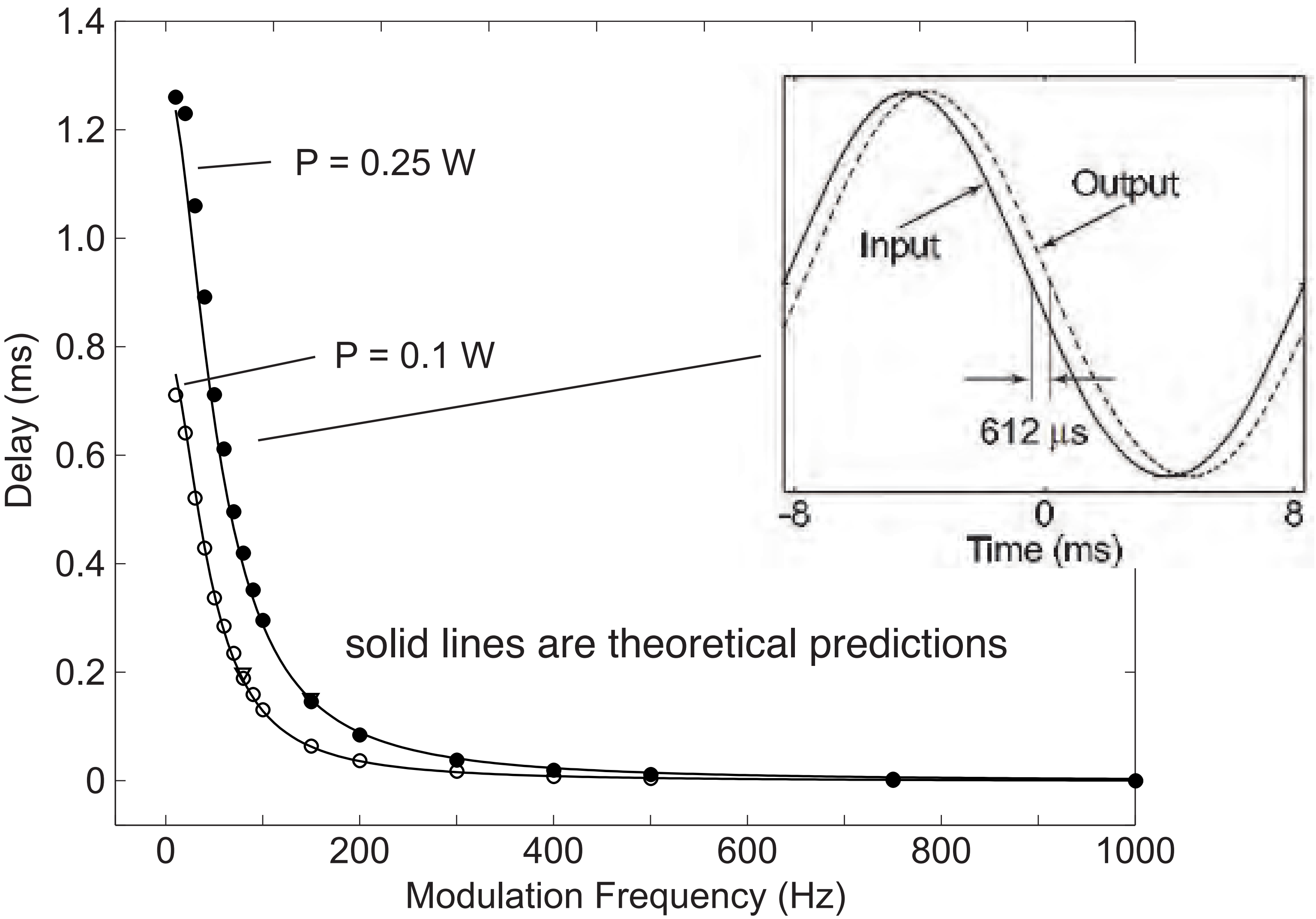
Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

Slow Light Experimental Setup



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

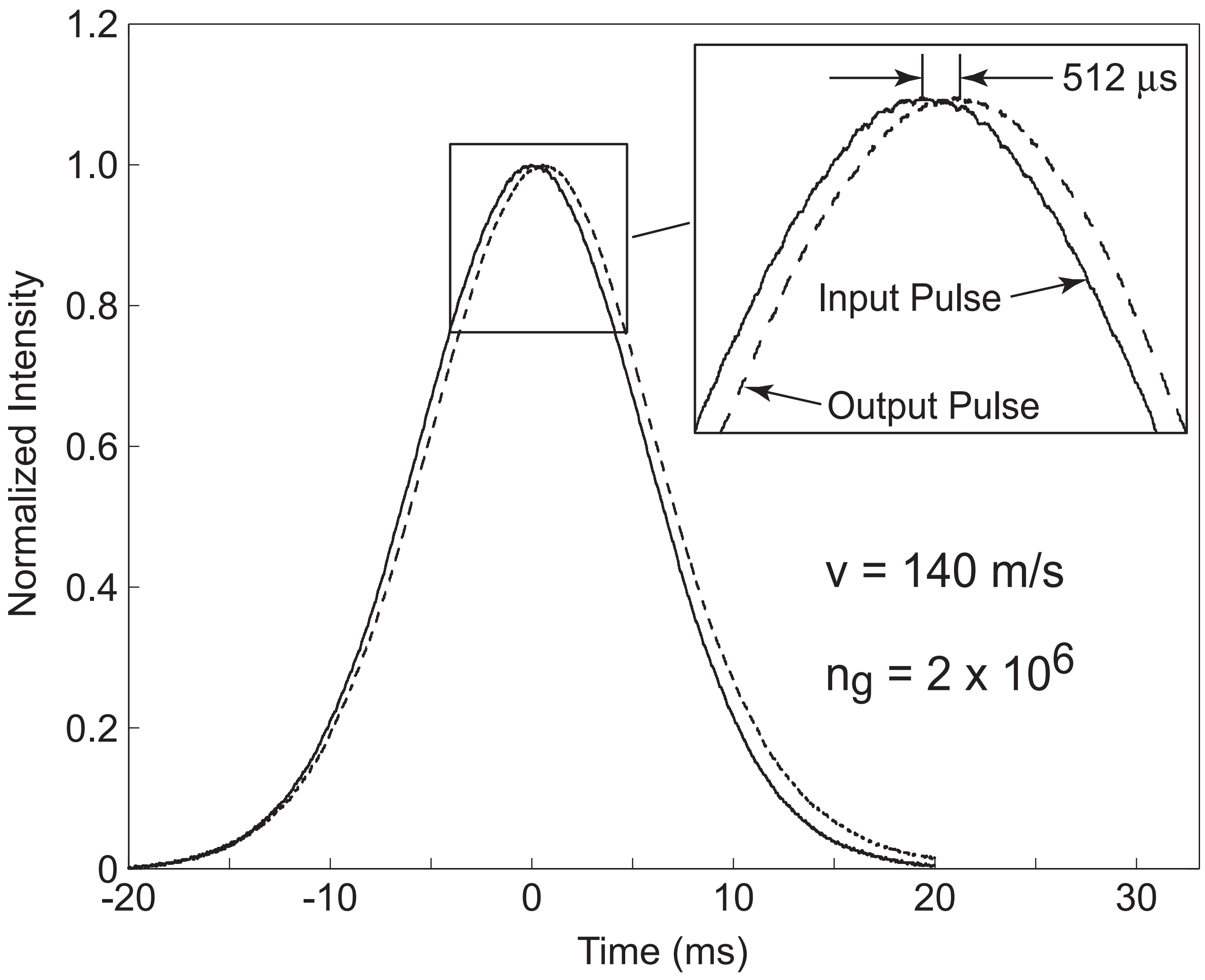
Measurement of Delay Time for Harmonic Modulation



solid lines are theoretical predictions

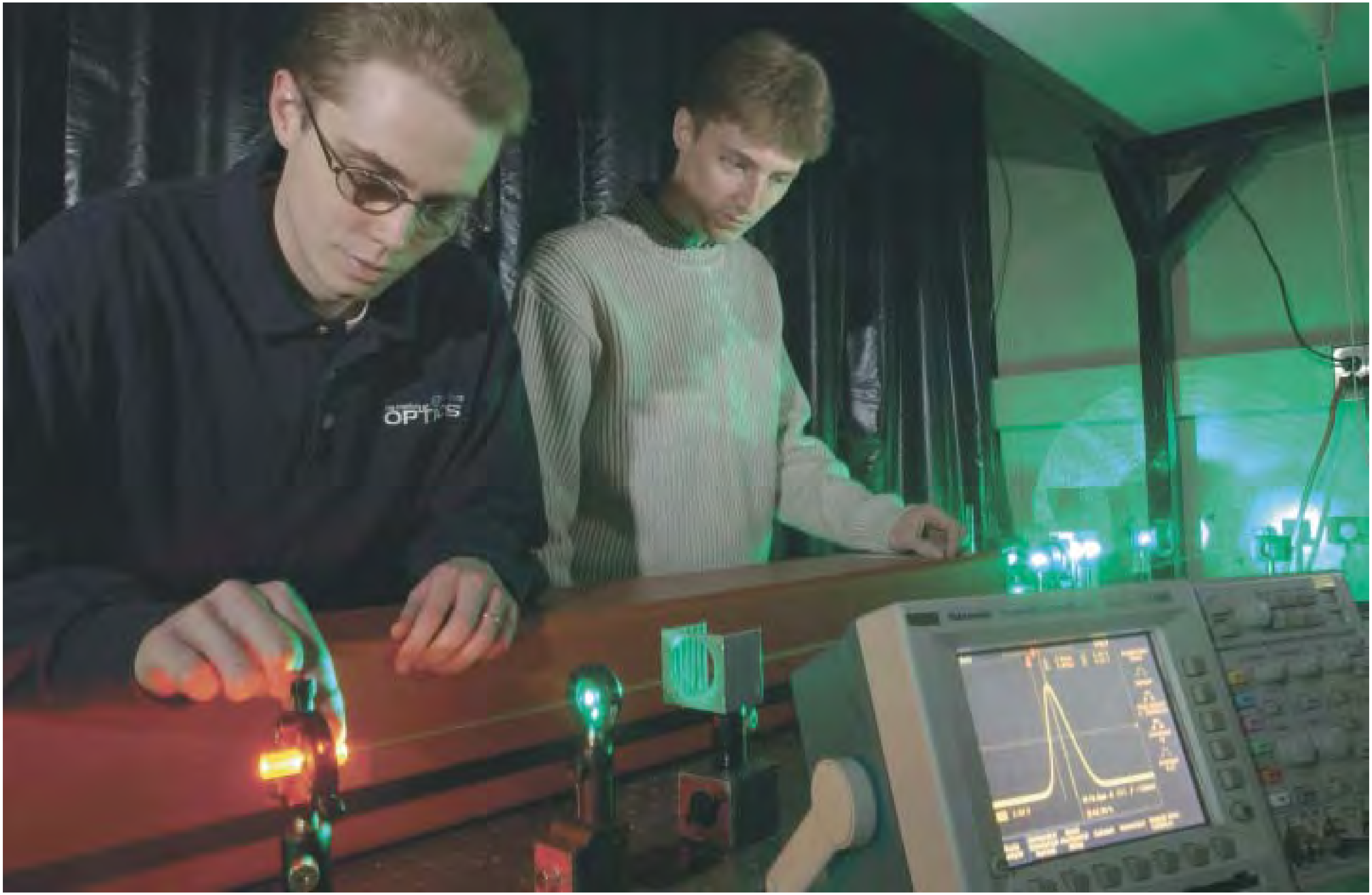
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

Gaussian Pulse Propagation Through Ruby



No pulse distortion!

Matt Bigelow and Nick Lepeshkin in the Lab



Advantages of Coherent Population Oscillations for Slow Light

Works in solids

Works at room temperature

Insensitive of dephasing processes

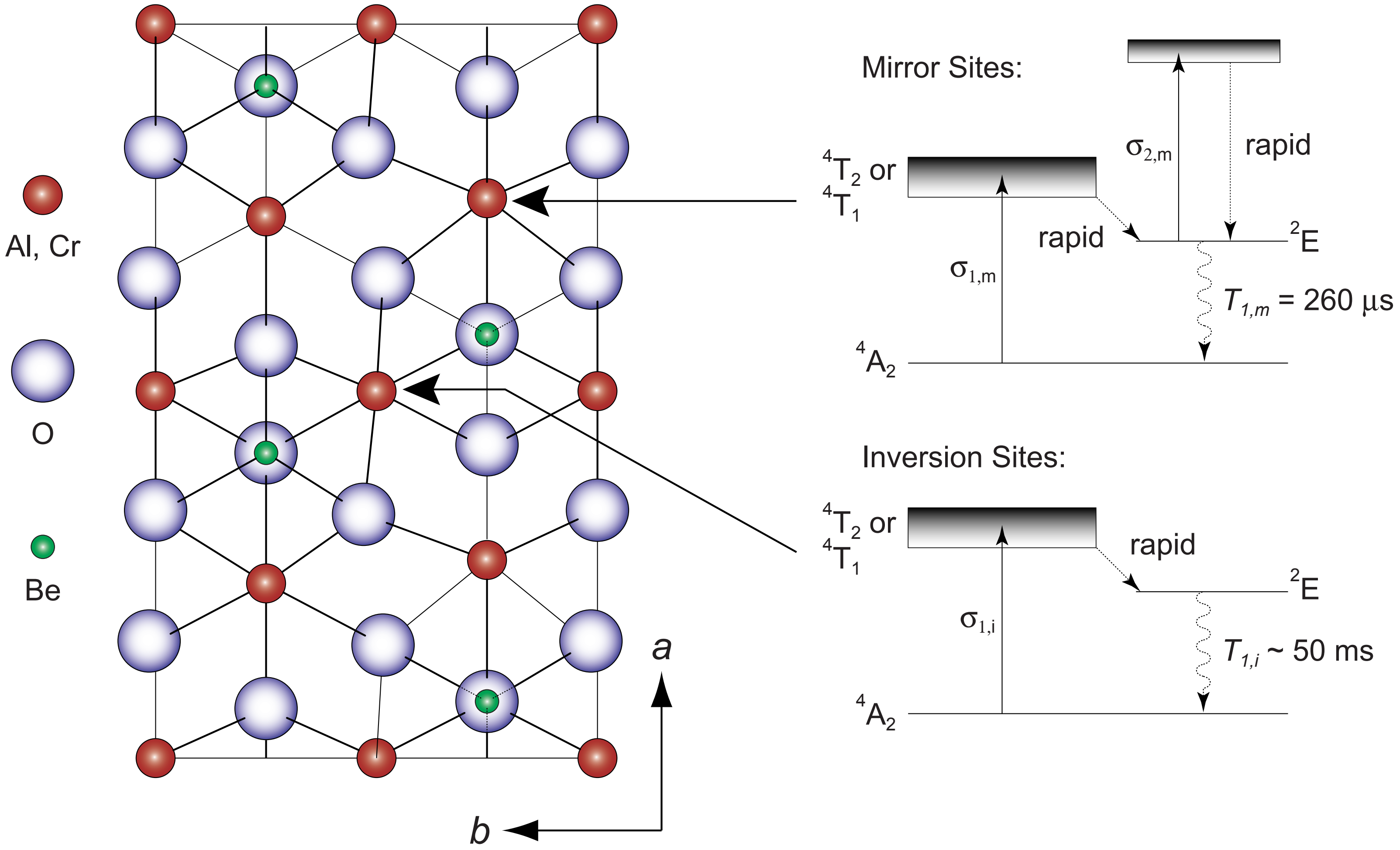
Laser need not be frequency stabilized

Works with single beam (self-delayed)

Delay can be controlled through input intensity

Alexandrite Displays both Saturable and Reverse-Saturable Absorption

- Both slow and fast propagation observed in alexandrite

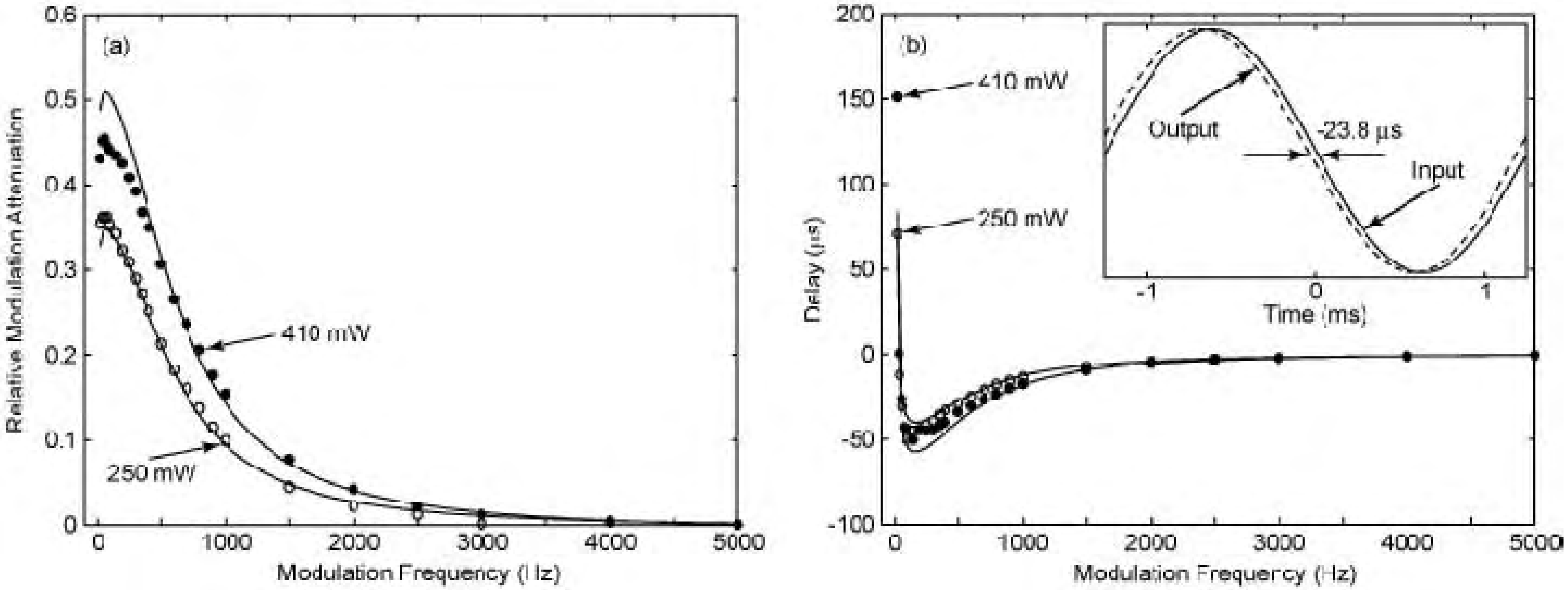


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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 paraxial 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.

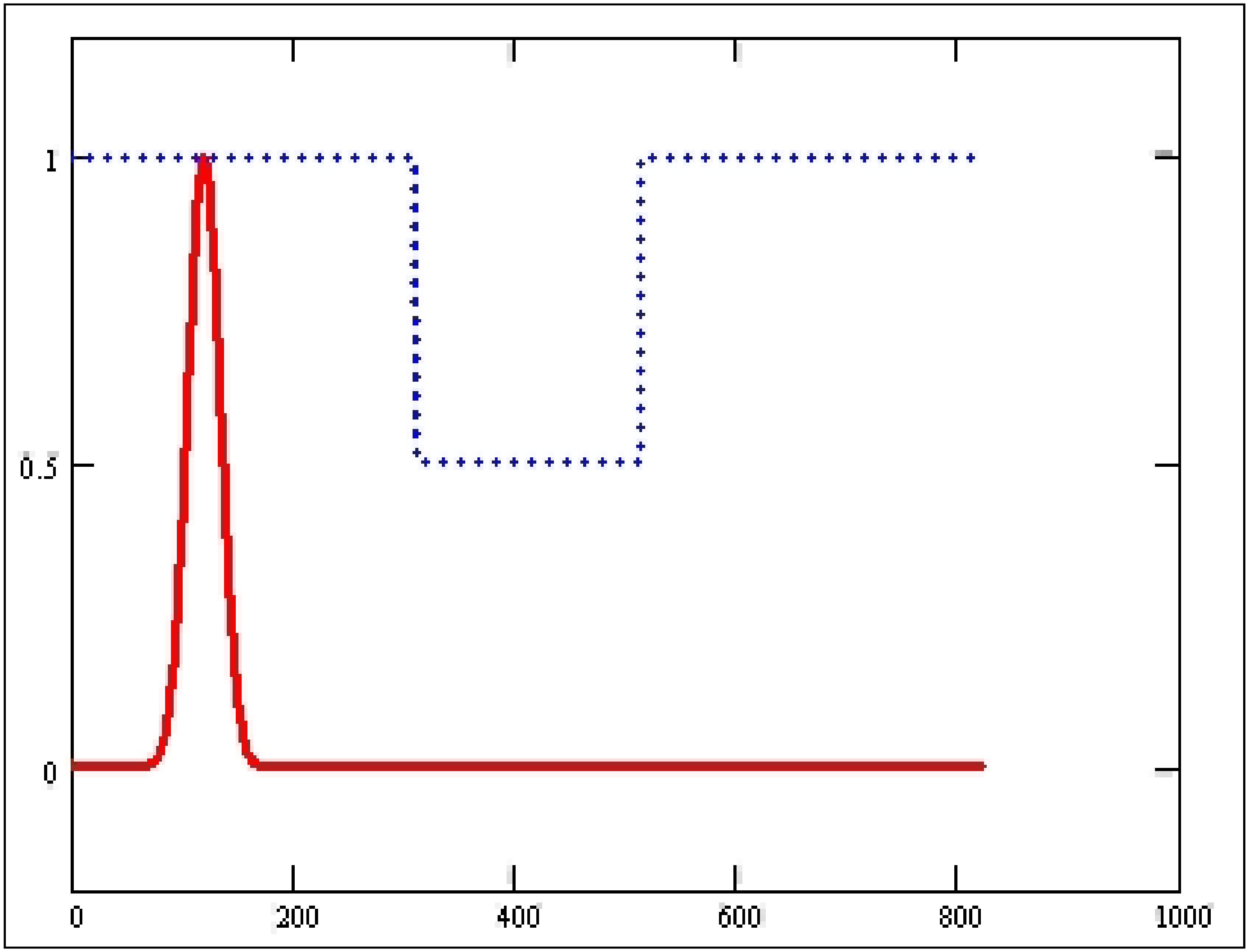
Assume an input pulse with a Gaussian temporal profile.

Study three cases:

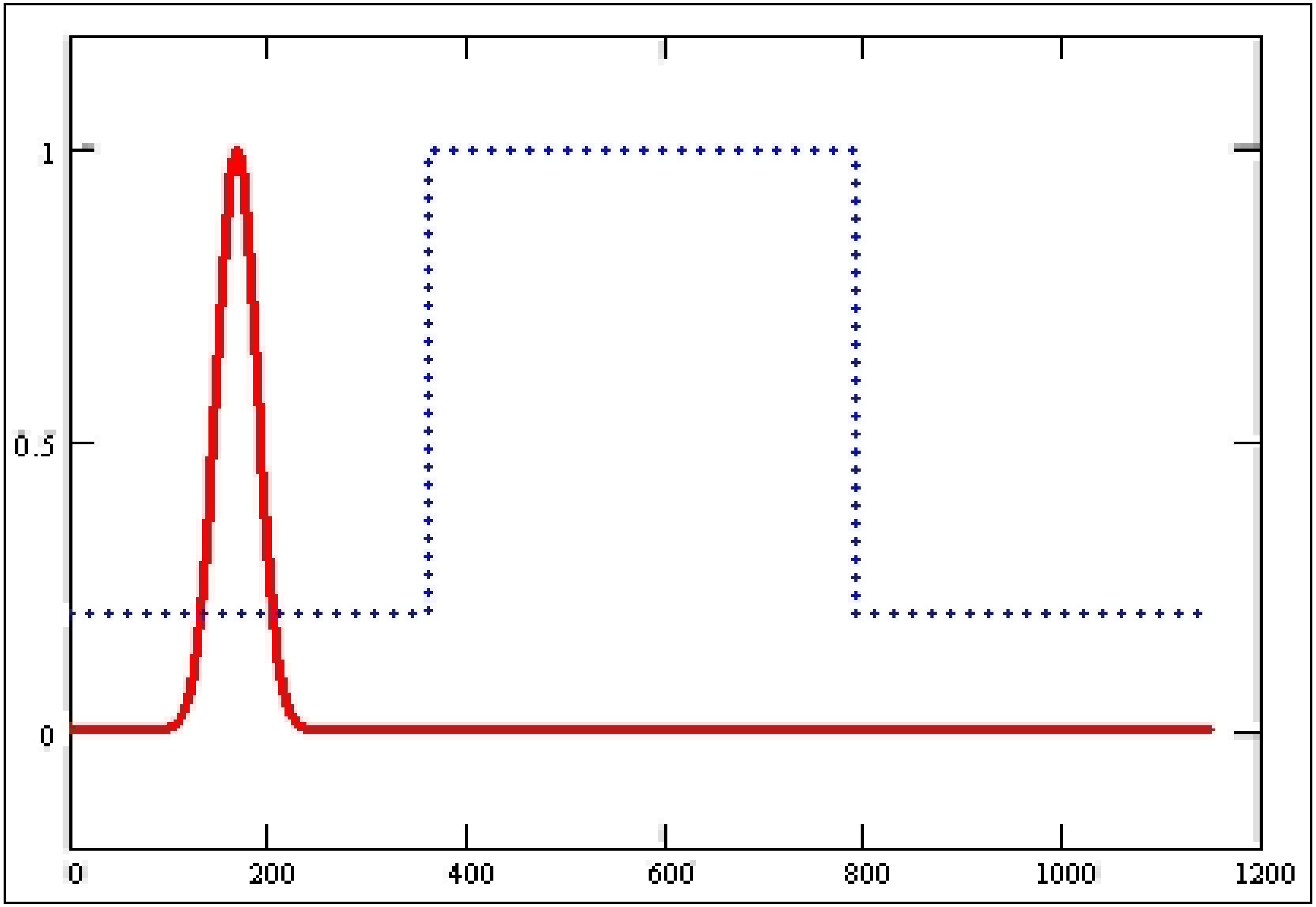
Slow light $v_g = 0.5\ c$

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

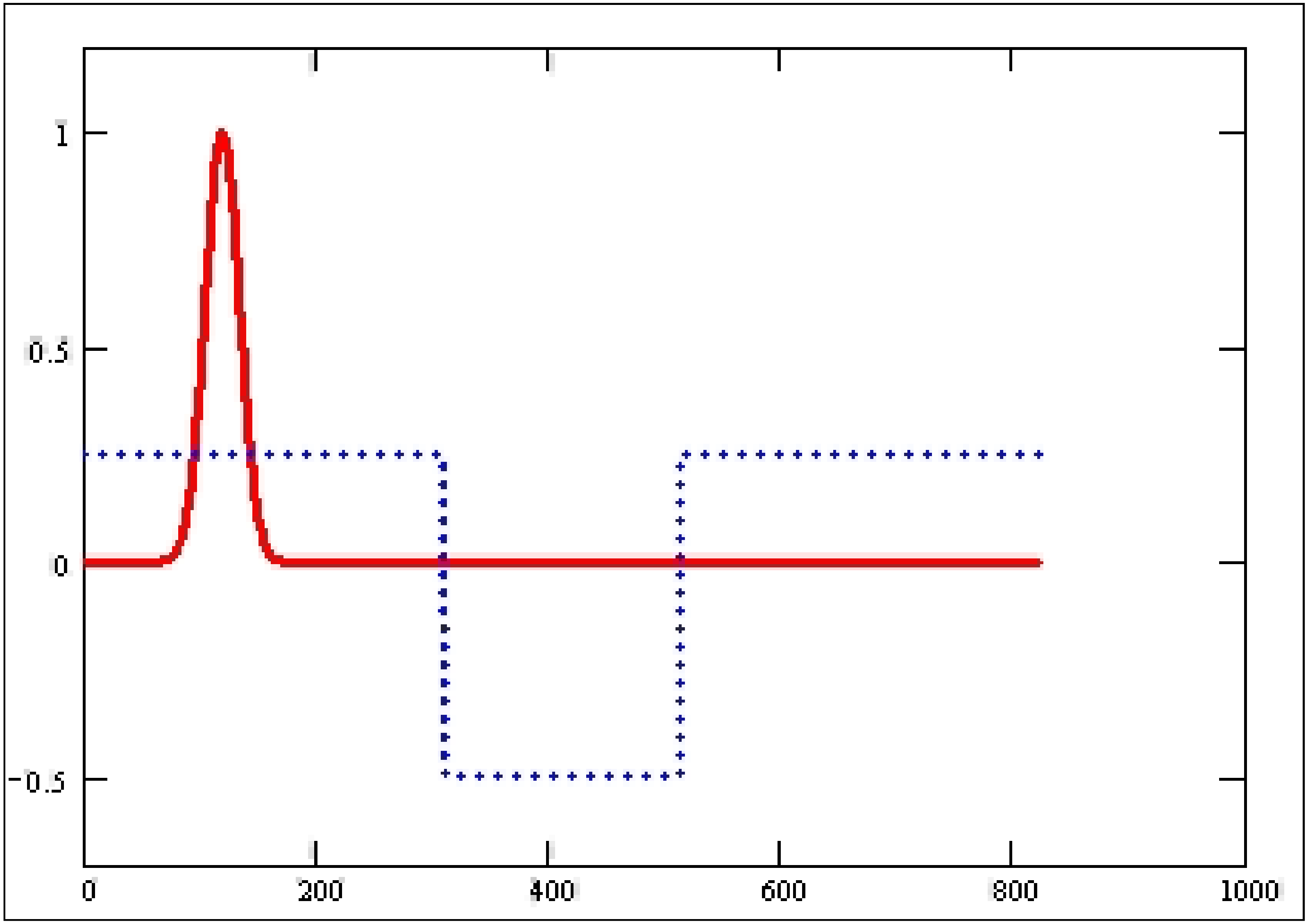
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



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



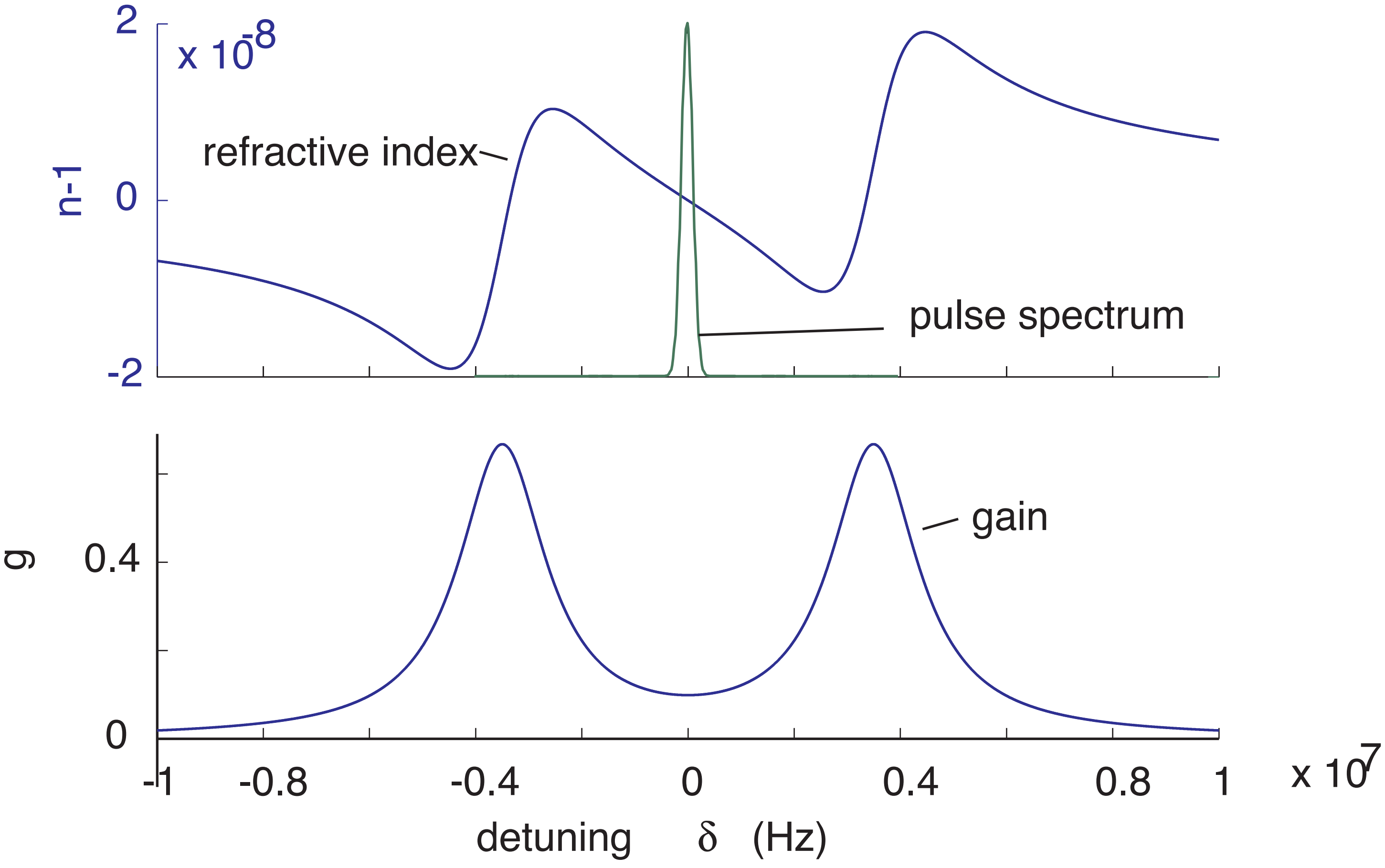
Pulse Propagation through a Fast-Light Medium (n_g = -.5, v_g = -2 c)



Are these predictions physical?
(We simply postulated a negative group velocity)

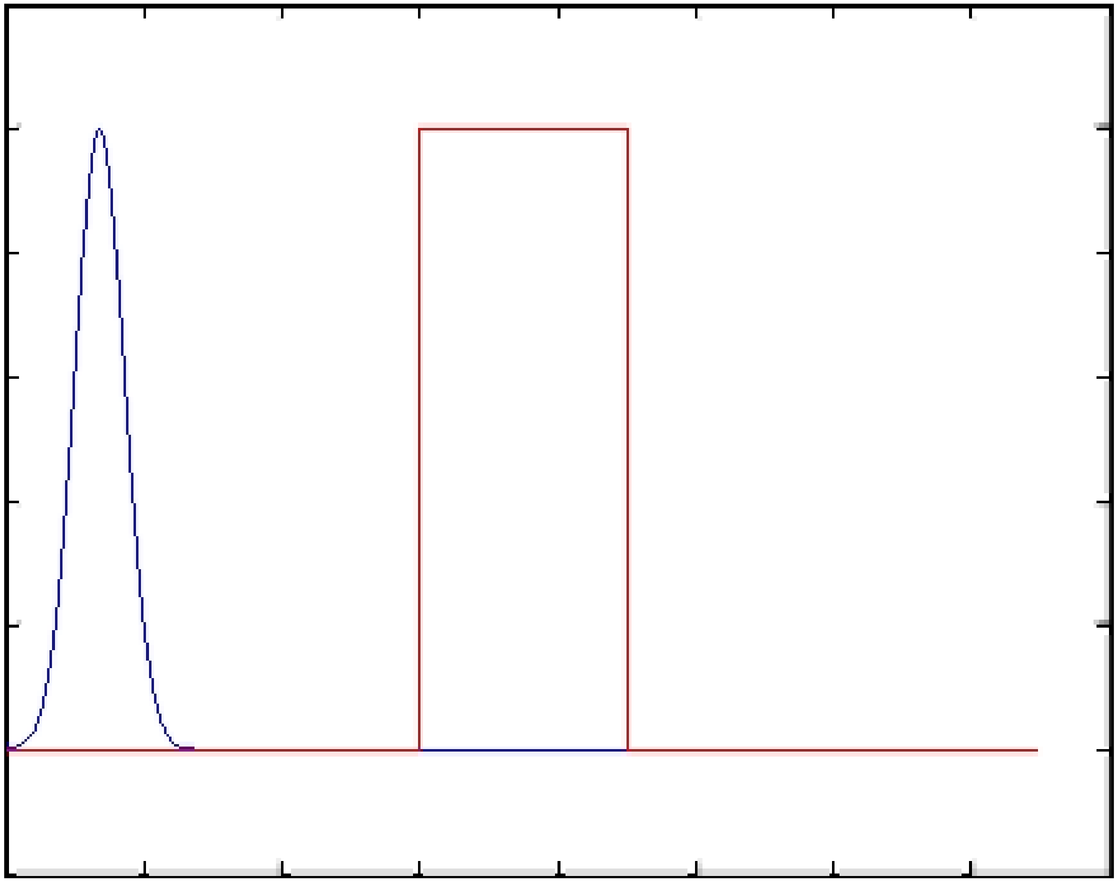
Consider a causal medium, for which Re *n* and Im *n* obey KK relations

Treat a gain doublet, which leads to superluminal effects*



* see also Chiao, Steinberg, Wang, Kuzmich, Gauthier, etc.

Superluminal Pulse Propagation through a Causal Medium



$$\chi(\omega) = \frac{A}{(\omega_0 - \Delta\omega) - \omega - i\Gamma} + \frac{A}{(\omega_0 + \Delta\omega) - \omega - i\Gamma} \quad - i\,\chi_{\mathrm{NR}}$$

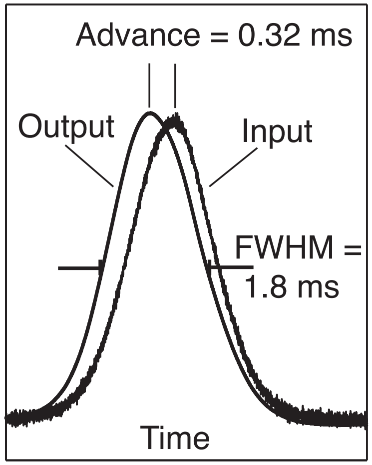
$\Gamma = (2\pi)\ 1.1\ \mathrm{MHz}$ $\quad A = 50\ /\ \mathrm{s}$

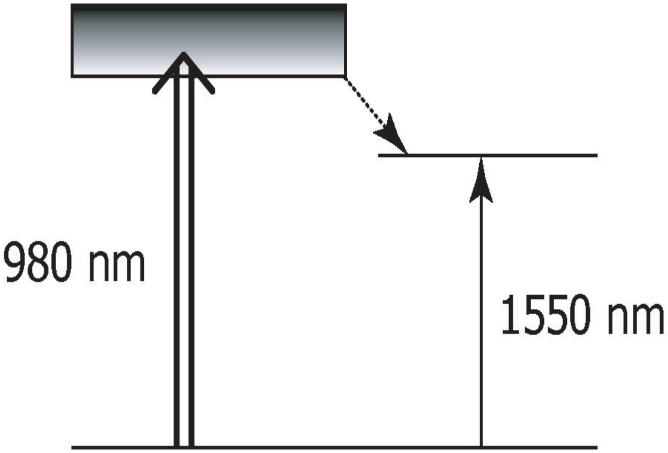
$\Delta\omega\ =\ (2\pi)\ 6\ \mathrm{MHz}$ = half frequency separation of gain lines

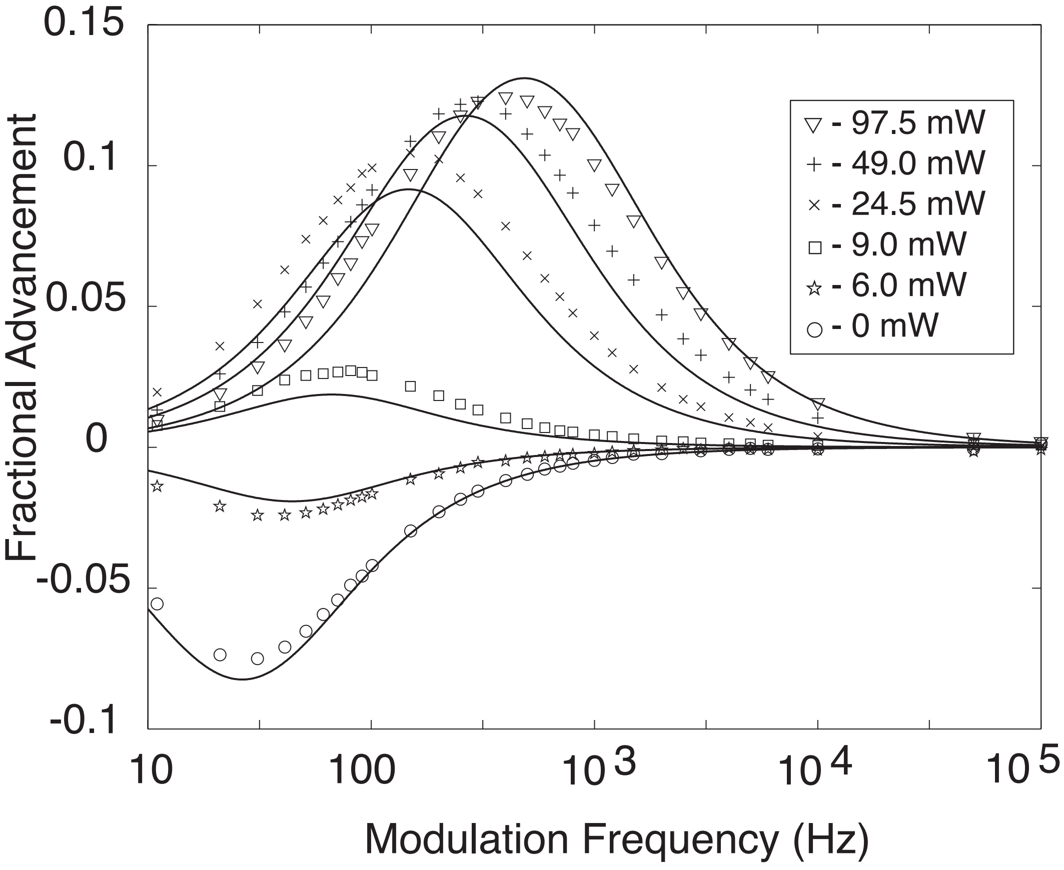
$n_{\mathrm{g}} = -\,642$ $\quad L = 2.9\ \mathrm{m}$ $\quad$ pulse duration = $10\ \mu\mathrm{s}$

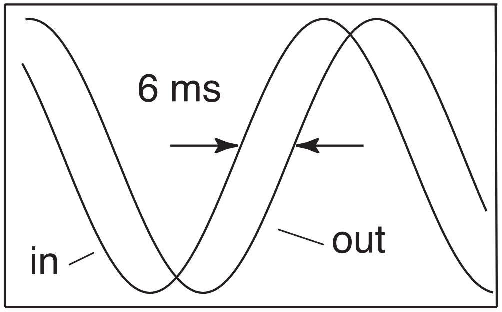
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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



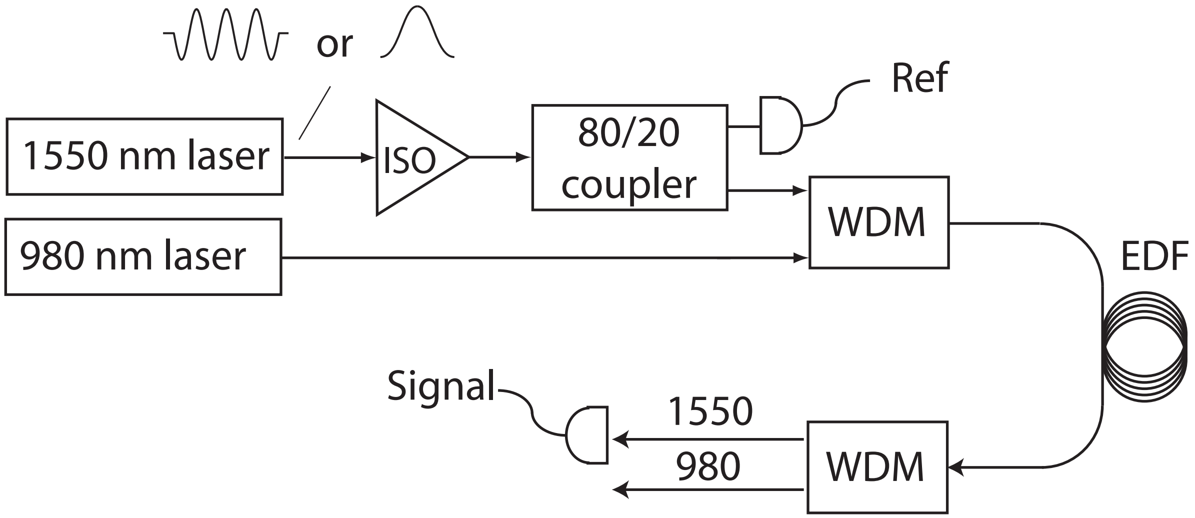






Schweinsberg, Lepeshkin, Bigelow, Boyd, and Jarabo

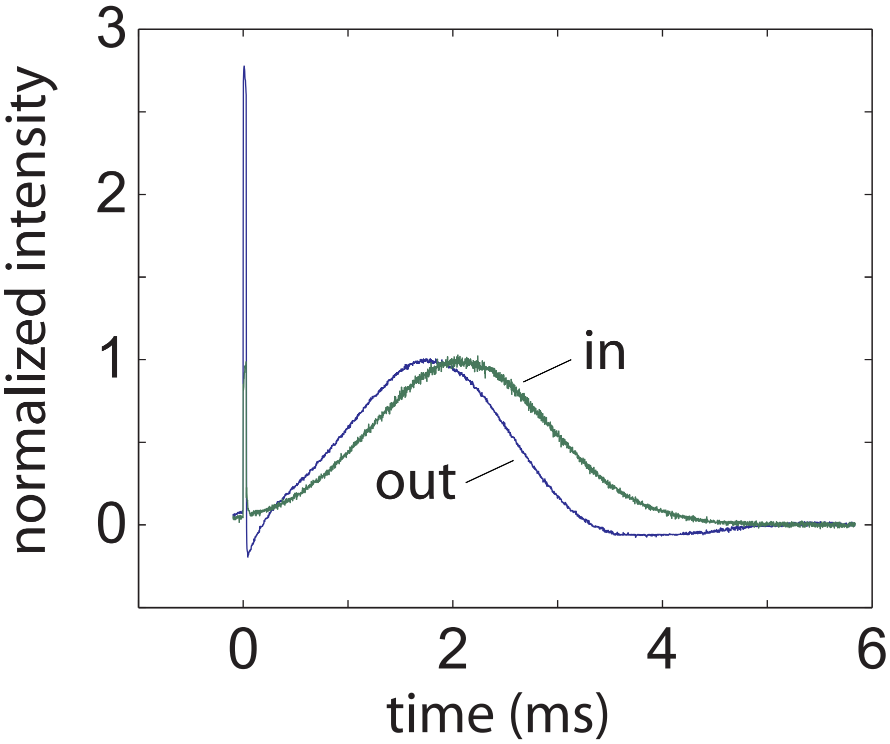
Observation of Backward Pulse Propagation in an Erbium-Doped-Fiber Optical Amplifier



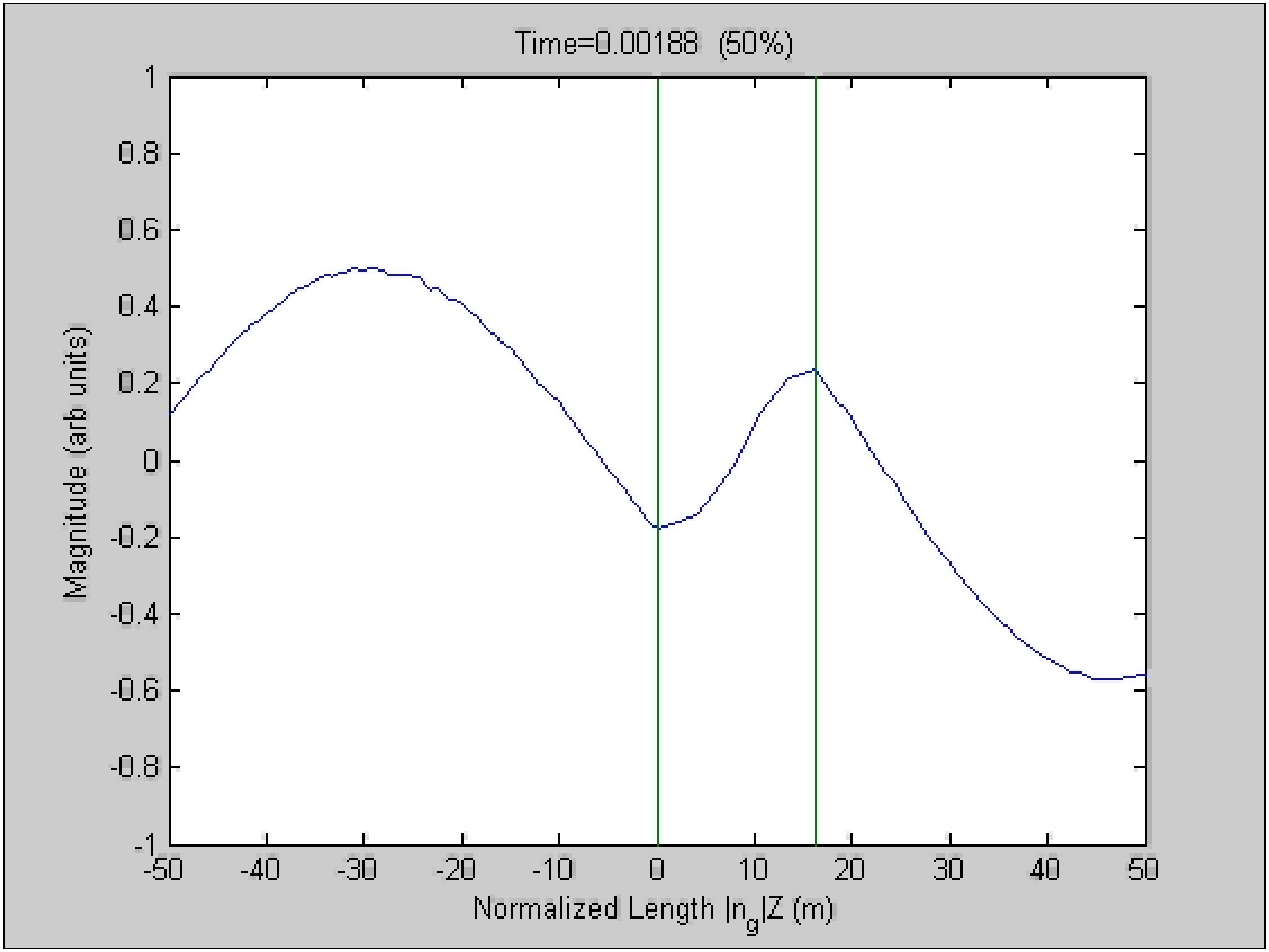
We time-resolve the propagation of the pulse as a function of position along the erbium-doped fiber.

Procedure

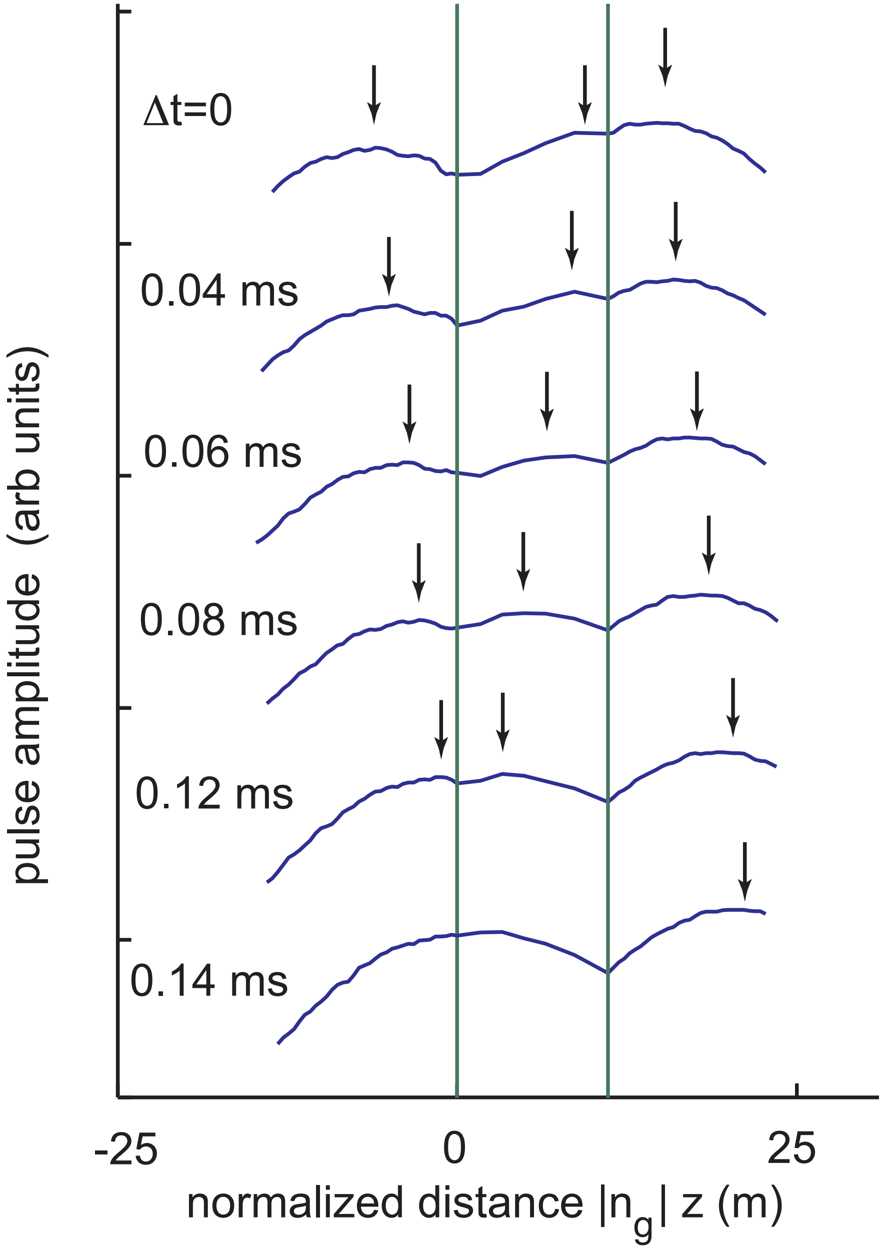
- cutback method
- couplers embedded in fiber



Experimental Results: Backward Propagation in Erbium-Doped Fiber



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:

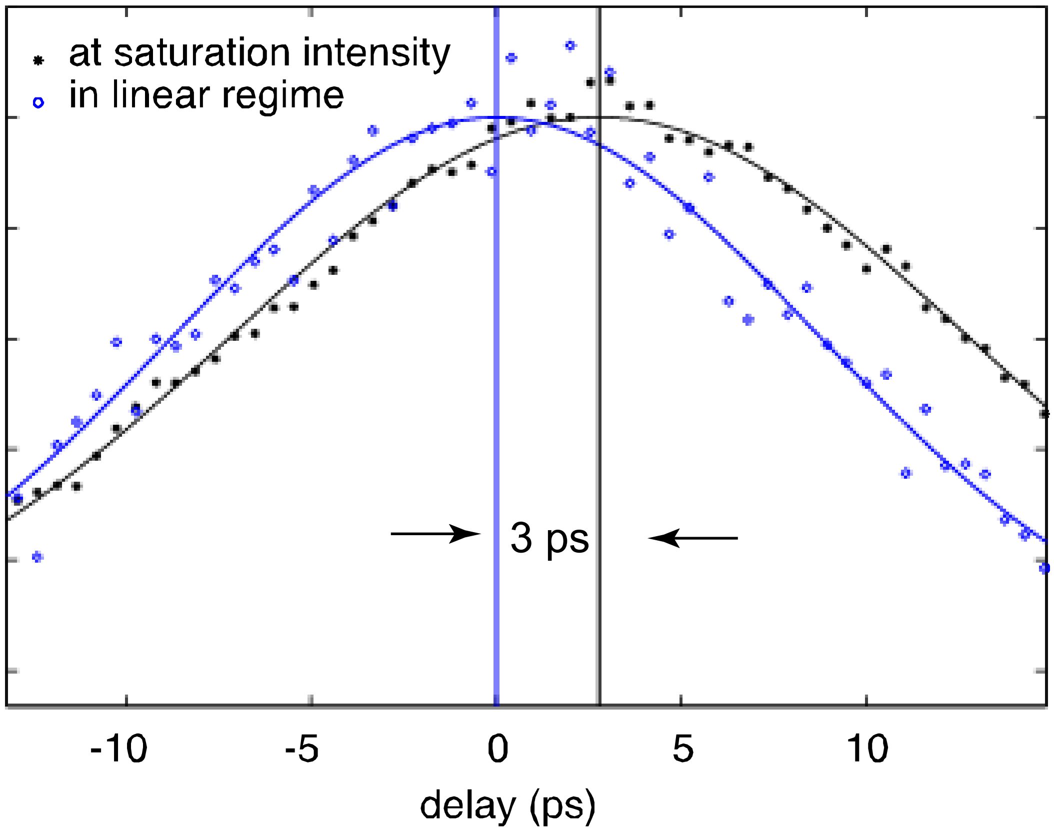
“Backwards” propagation is a realizable physical effect.

Slow Light in SC Quantum Dot Structures

PbS Quantum Dots (2.9 nm diameter) in liquid solution

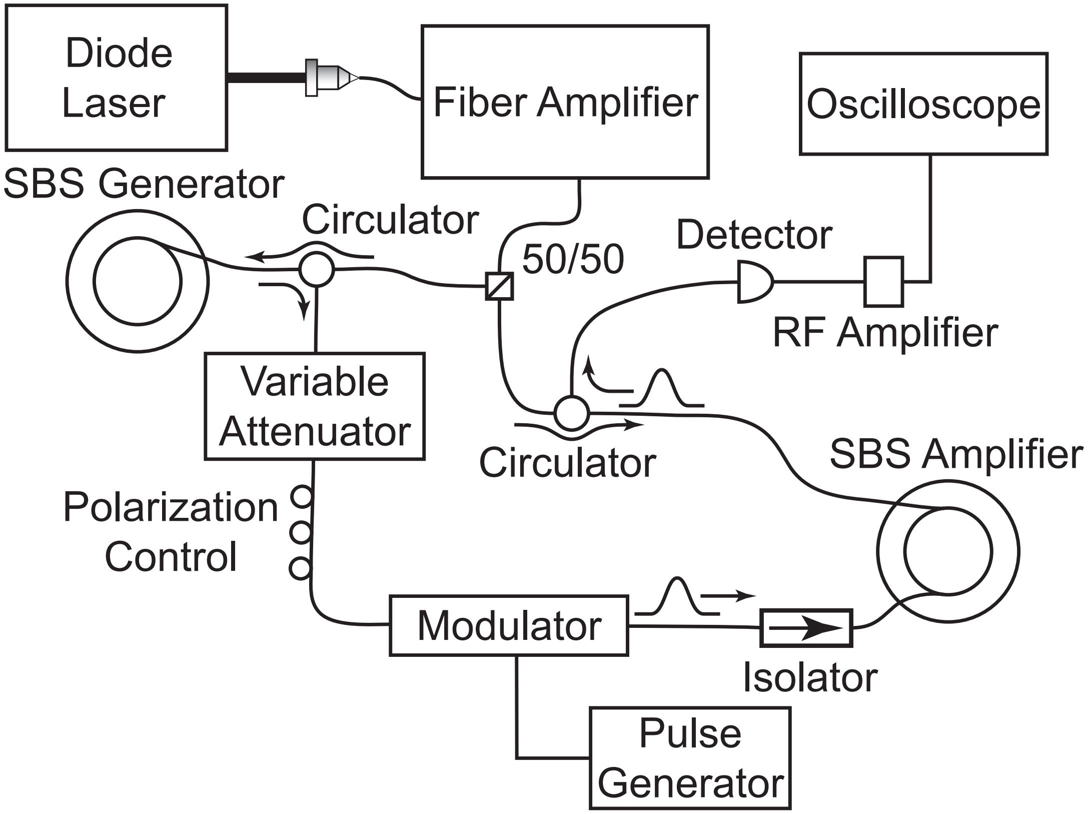
Excite with 16 ps pulses at 795 nm; observe 3 ps delay

30 ps response time (literature value)

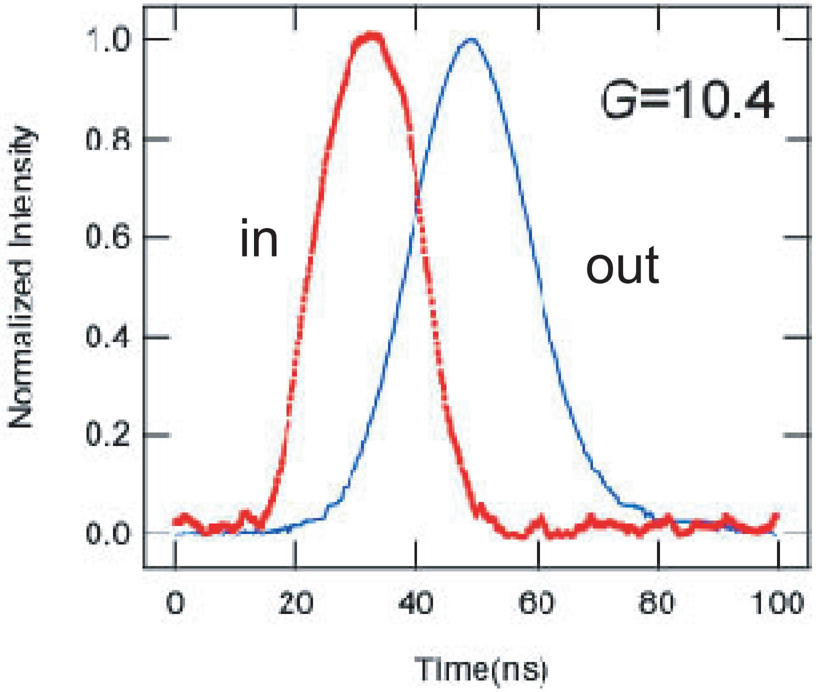


Slow-Light via Stimulated Brillouin Scattering

- 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).

Summary

Slow-light techniques hold great promise for applications in telecom and quantum information processing

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

Different methods under development possess complementary regimes of usefullness

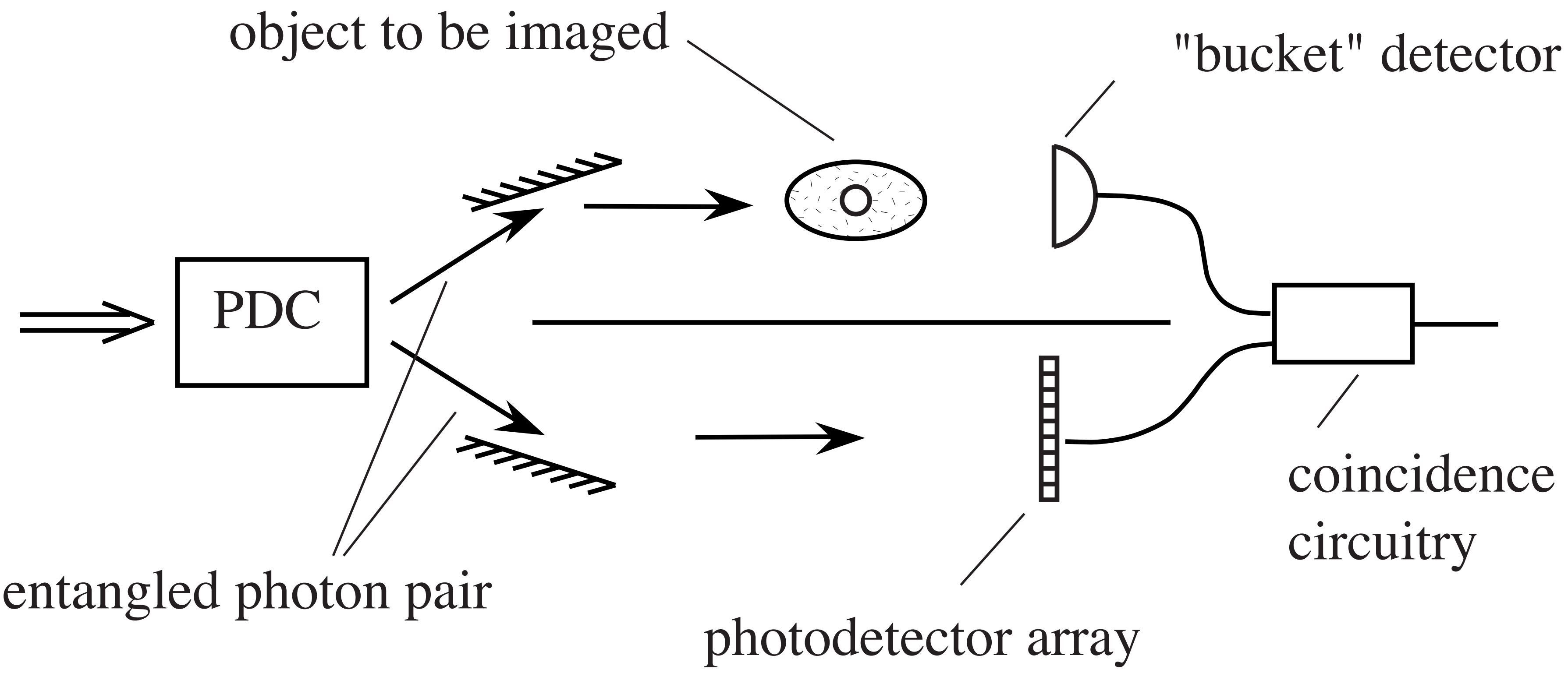
Research in Quantum Imaging

Can images be formed with higher resolution or better sensitivity through use of quantum states of light?

Can we "beat" the Rayleigh criterion?

Quantum states of light: For instance, squeezed light or entangled beams of light.

Ghost (Coincidence) Imaging



- Obvious applicability to remote sensing!
- Is this a purely quantum mechanical process?

Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).
Bennink, Bentley, Boyd, and Howell, PRL 92 033601 (2004)
Gatti, Brambilla, and Lugiato, PRL 90 133603 (2003)
Gatti, Brambilla, Bache, and Lugiato, PRL 93 093602 (2003)

Progress in Quantum Lithography

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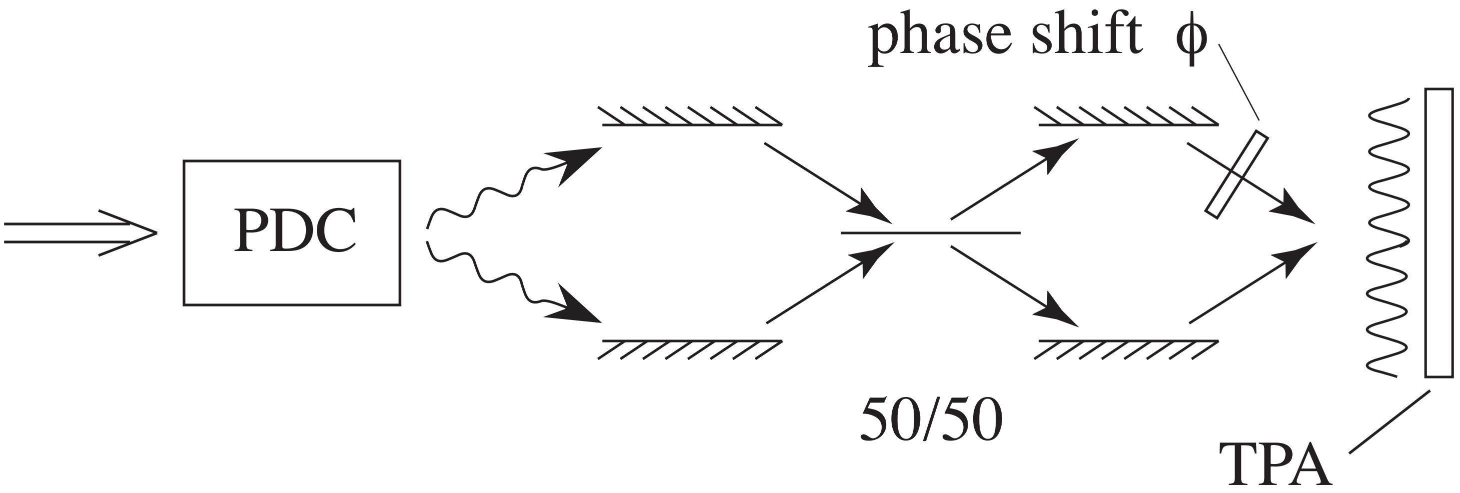
Quantum Lithography

- Entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit
- Process "in reverse" performs sub-Rayleigh microscopy, etc.
- Resolution ≈ $\lambda / 2N$, where N = number of entangled photons



Boto et al., Phys. Rev. Lett. 85, 2733, 2000.

("al." includes Jon Dowling)

Quantum Lithography: Easier Said Than Done

- Need an intense source of individual biphotons (Inconsistency?)

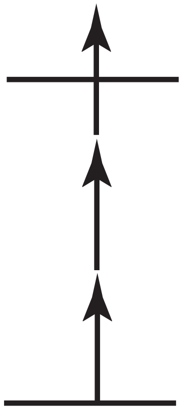
  Maybe a high-gain OPA provides the best tradeoff between high intensity and required quantum statistics

- Need an *N*-photon recording material

For proof-of-principle studies, can use *N*-th-harmonic generator, correlation circuitry, *N*-photon photodetector.

For actual implementation, use ????

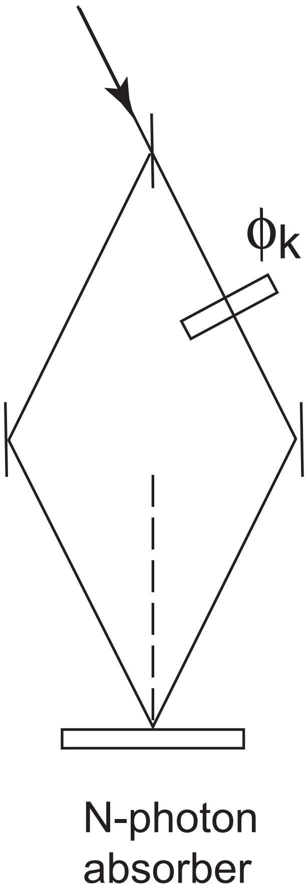
Maybe best bet is UV lithographic material excited in the visible or a broad bandgap material such as PMMA excited by multiphoton absorption.

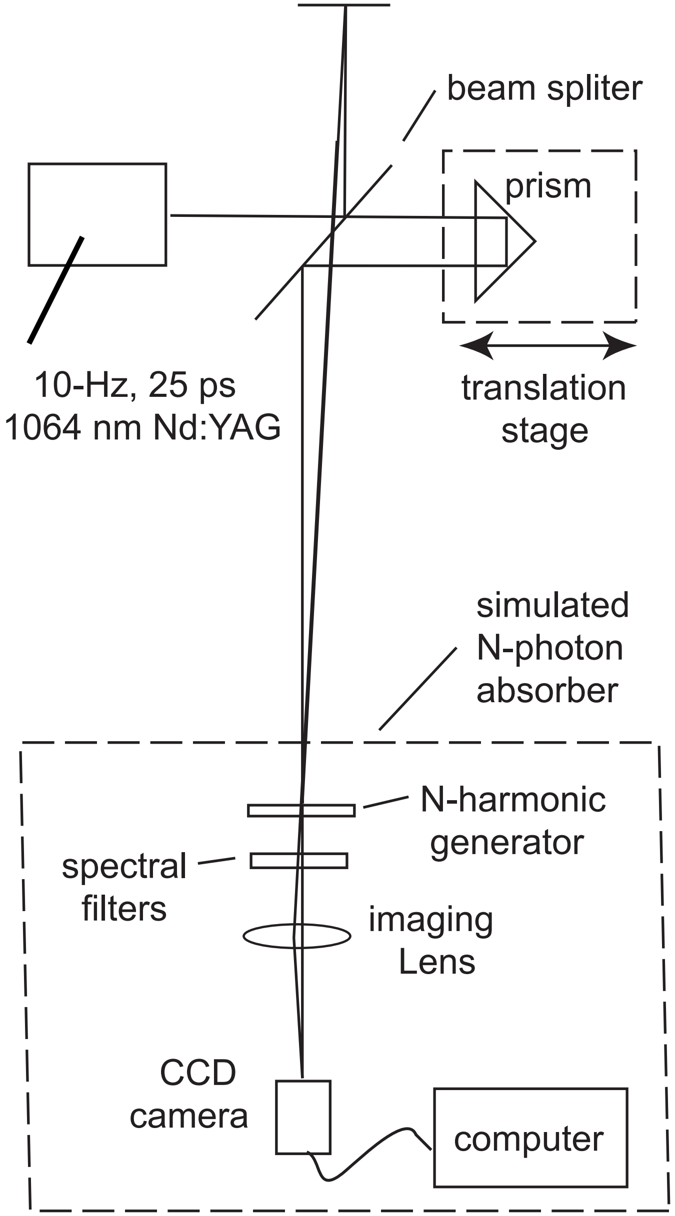


3PA in PMMA breaks chemical bond, modifying optical properties.

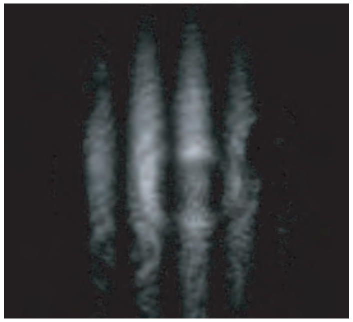
Non-Quantum Quantum Lithography

Concept: average M shots with the phase of shot k given by $2\pi k/M$

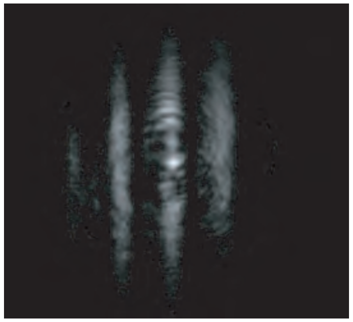




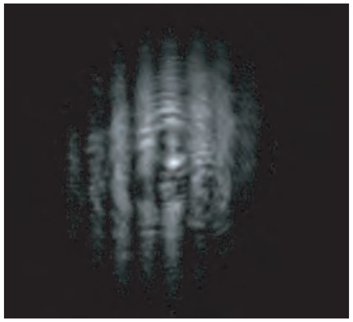
N=1, M=1



N=2, M=1

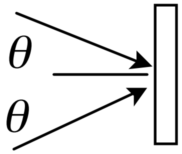


N=2, M=2



S. J. Bentley and R.W. Boyd, Optics Express, 12, 5735 (2004).

Spatial Resolution of Various Systems



- Linear optical medium

$$E = 1 + \cos kx$$

- Two-photon absorbing medium, classical light

$$E = (1 + \cos kx)^2 = 1 + 2 \cos kx + \cos^2 kx$$

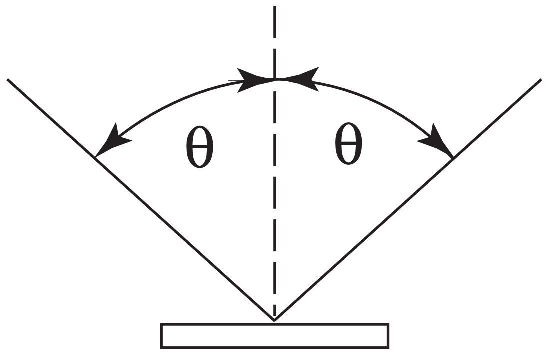
$$= 3/2 + 2 \cos kx + (1/2) \cos 2kx$$

- Two-photon absorbing medium, entangled photons

$$E = 1 + \cos 2kx$$

where $k = 2(\omega/c) \sin \theta$

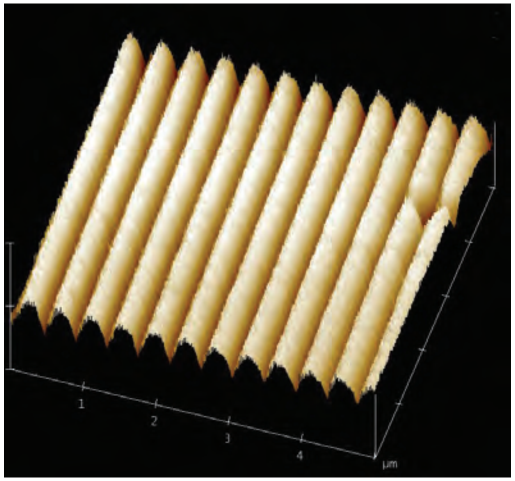
Demonstration of Fringes Written into PMMA



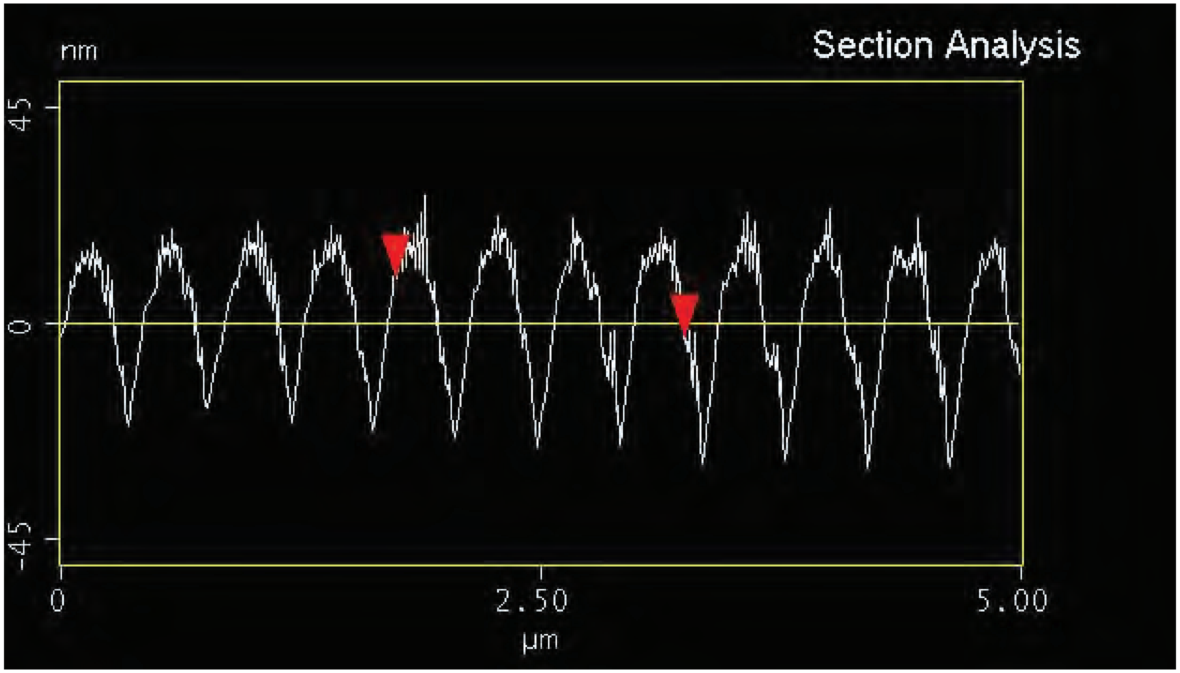
N-photon absorber
(N = 3 ?)

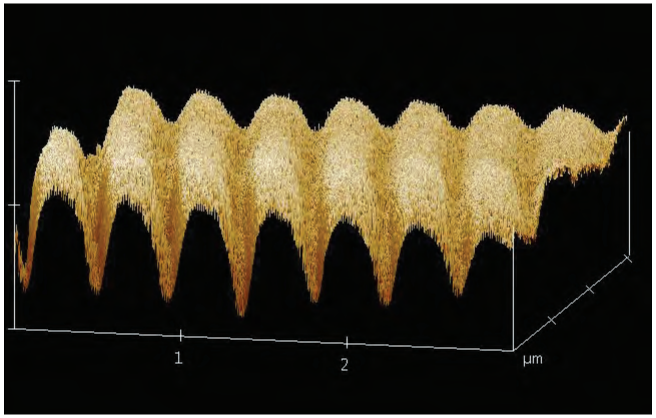
θ = 70 degrees
write wavelength = 800 nm
pulse energy = 130 μJ per beam
pulse duration = 120 fs
period = $\lambda / (2 \sin \theta)$ = 425 nm

PMMA on glass substrate
develop for 10 sec in MBIK
rinse 30 sec in deionized water



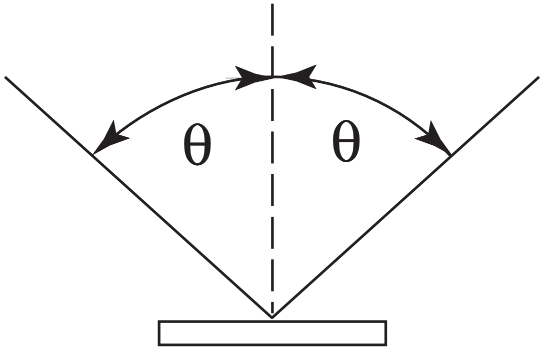
AFM





PMMA is a standard
lithographic material

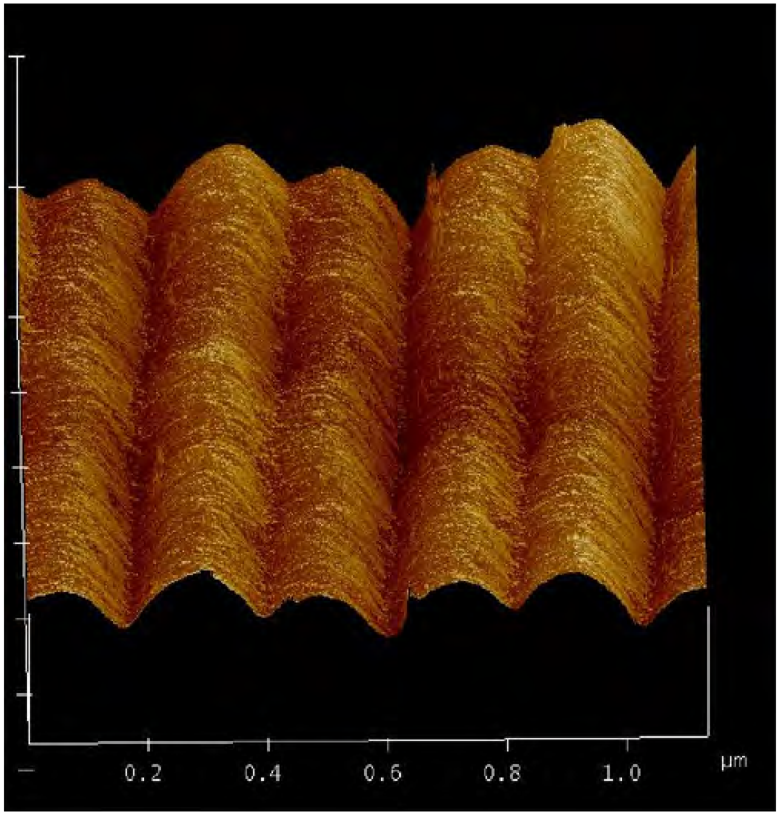
Demonstration of Sub-Rayleigh Fringes (Period = $\lambda/4$)

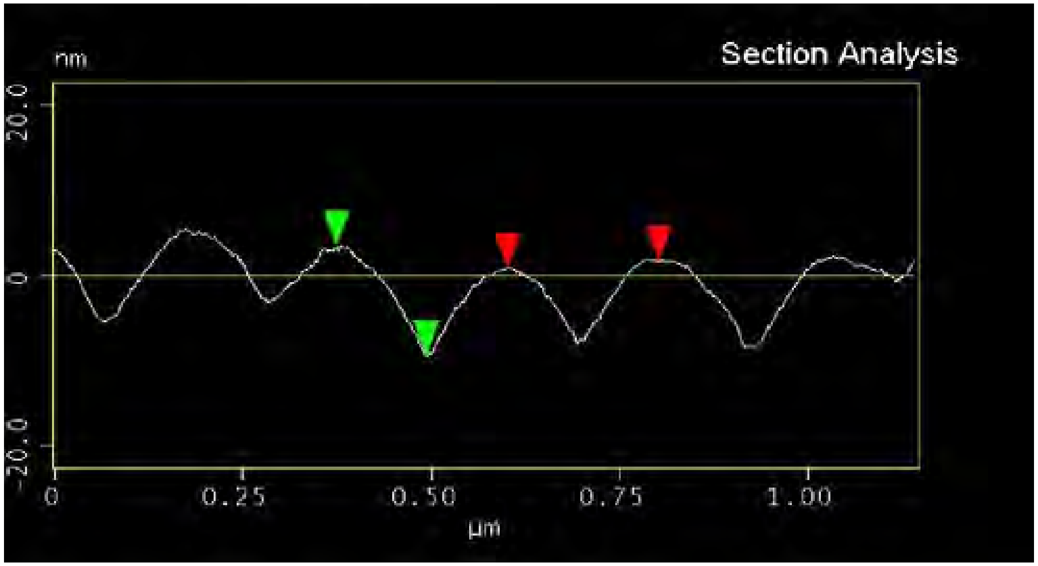


N-photon absorber

θ = 70 degrees
two pulses with 180 deg phase shift
write wavelength = 800 nm
pulse energy = 90 µJ per beam
fundamental period = $\lambda / (2 \sin \theta)$ = 425 nm
period of written grating = 212 nm

PMMA on glass substrate
develop for 10 sec in MBIK
rinse 30 sec in deionized water





Significance of PMMA Grating Results

- Provides an actual demonstration of sub-Rayleigh resolution by the phase-shifted grating method

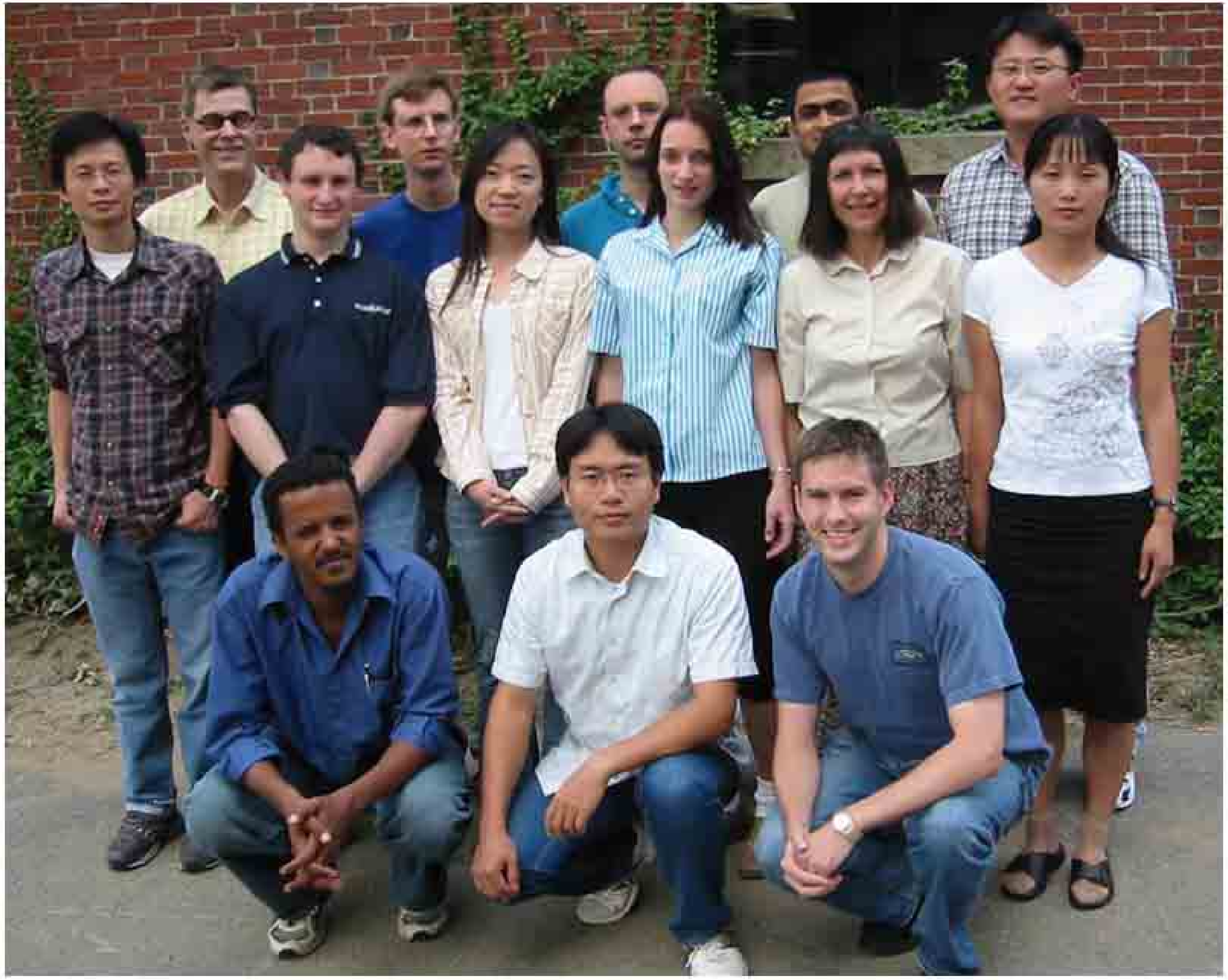
- Demonstrates an N-photon absorber with adequate resolution to be of use in true quantum lithography

Quantum Lithography Prospects

Quantum lithography (as initially proposed by Dowling) has a good chance of becoming a reality.

Classically simulated quantum lithography may be a realistic alternative approach, and one that is much more readily implemented.

Special Thanks to My Students and Research Associates



Thank you for your attention!

Our results are posted on the web at:

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