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 the Stanford Photonics Research Center, September 20, 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

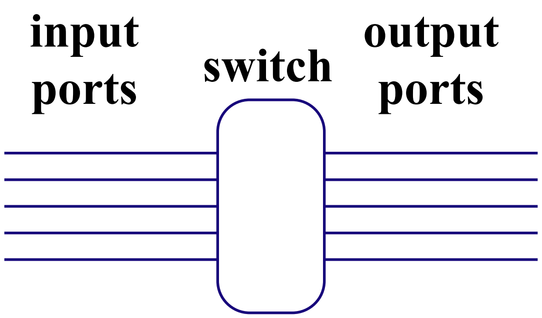
Implications for quantum information

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

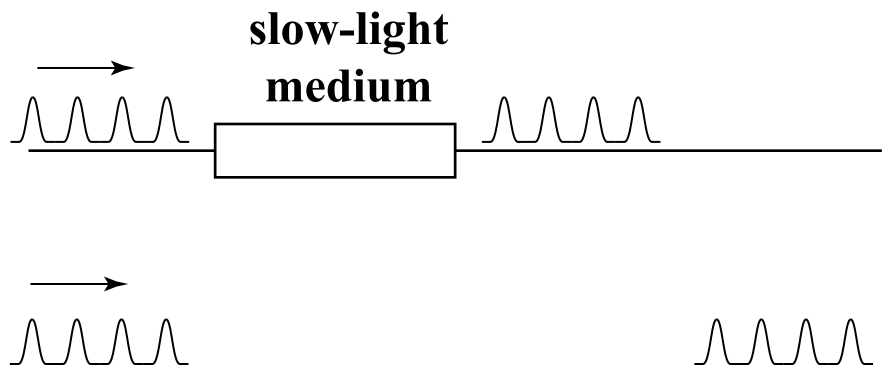
Boyd and Gauthier, "Slow and Fast Light," in Progress in Optics, 43, 2002.

Slow Light and Optical Buffers

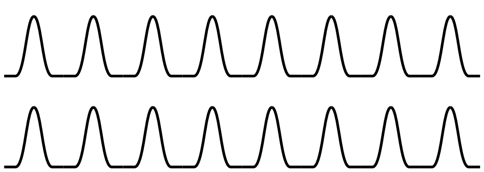
All-Optical Switch



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

Challenge/Goal

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

Possible approaches:

1. Slow light based on photonic crystals
2. Slow light based on stimulated light scattering

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

Slow Light in Ruby

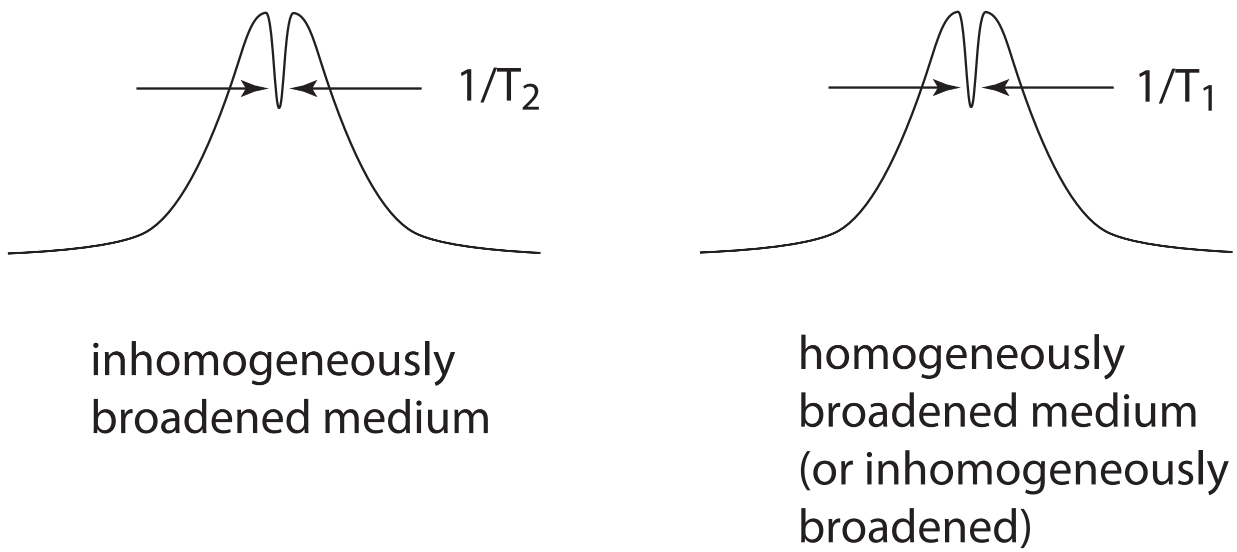
Recall that $n_g = n + \omega(dn/d\omega)$. Need a large $dn/d\omega$. (How?)

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.

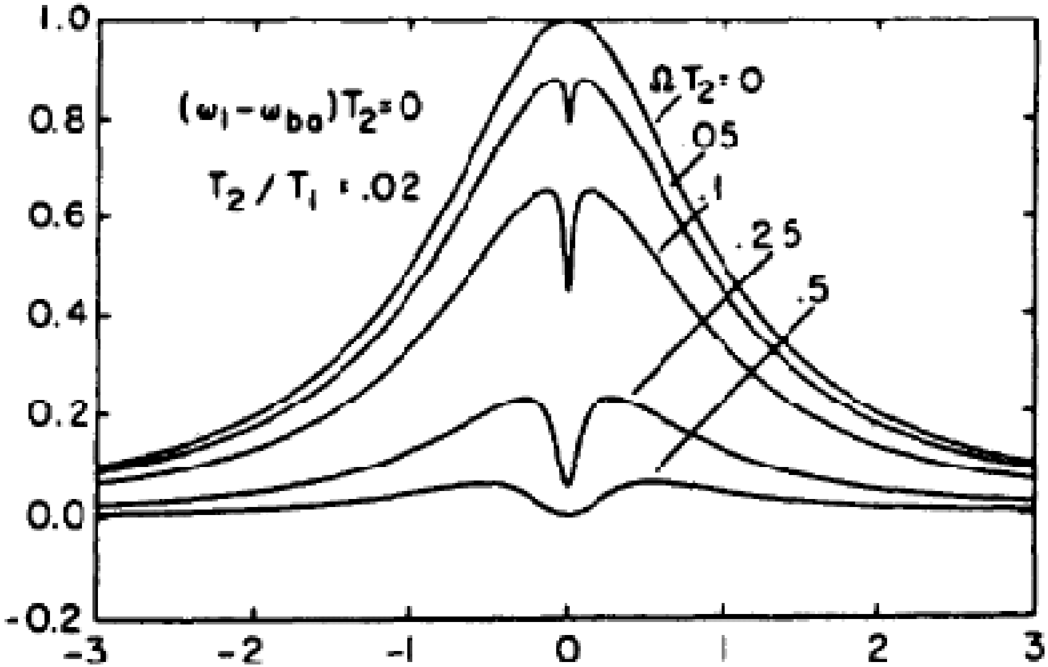
Hole-burning in a homogeneously broadened line; requires $T_2 << T_1$.



PRL 90,113903(2003).

Spectral Holes in Homogeneously Broadened Materials

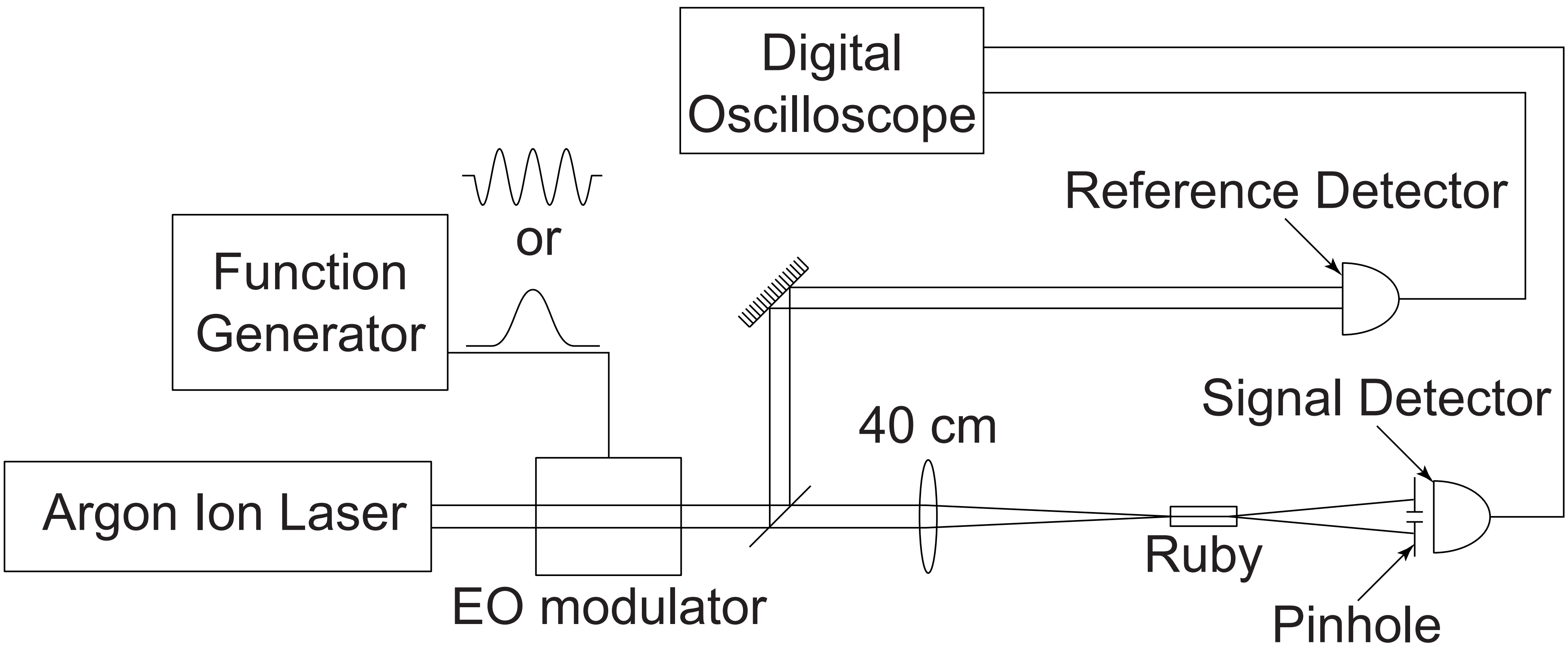
Occurs only in collisionally broadened media ($T_2 << T_1$)



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

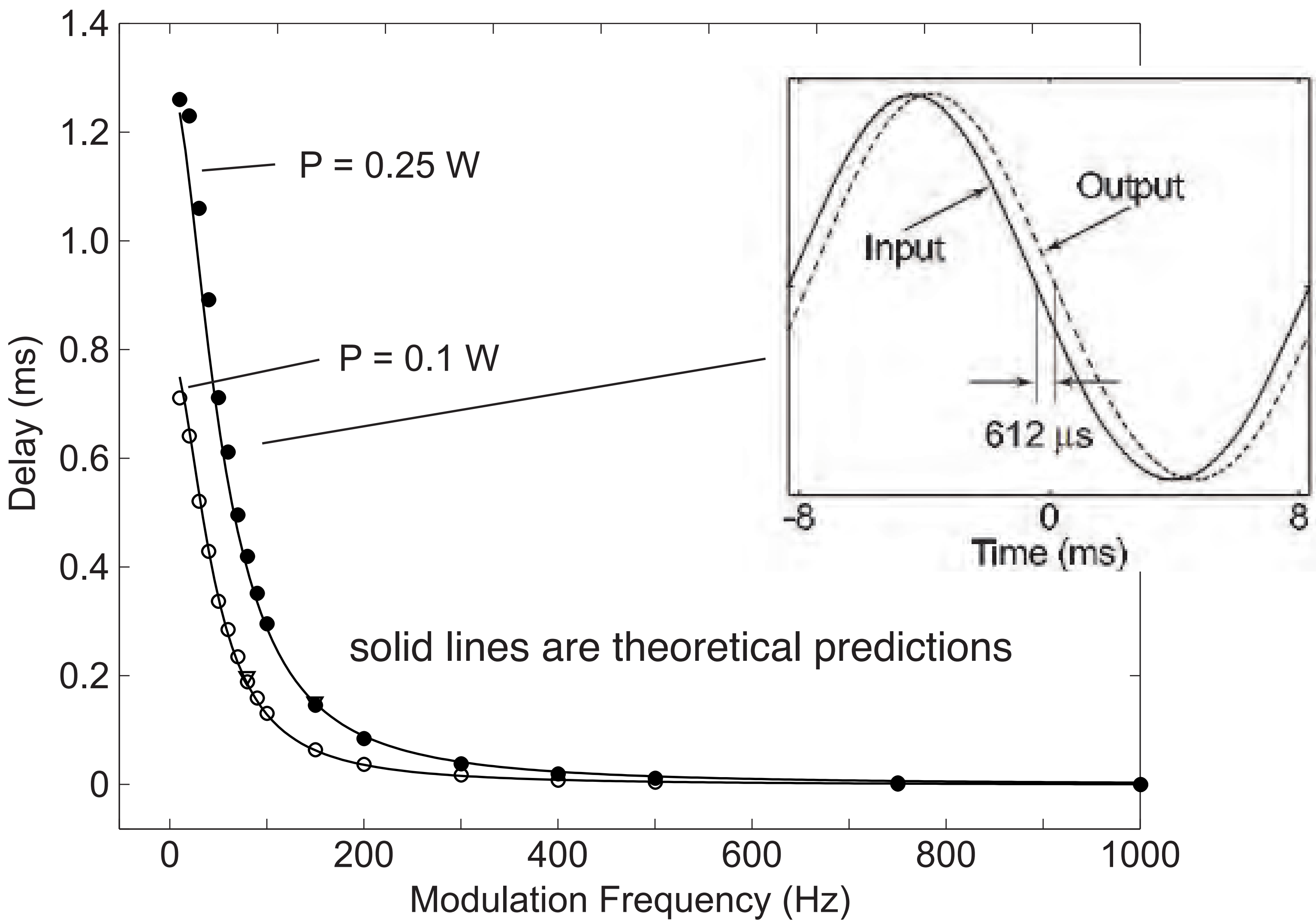
Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

Slow Light Experimental Setup



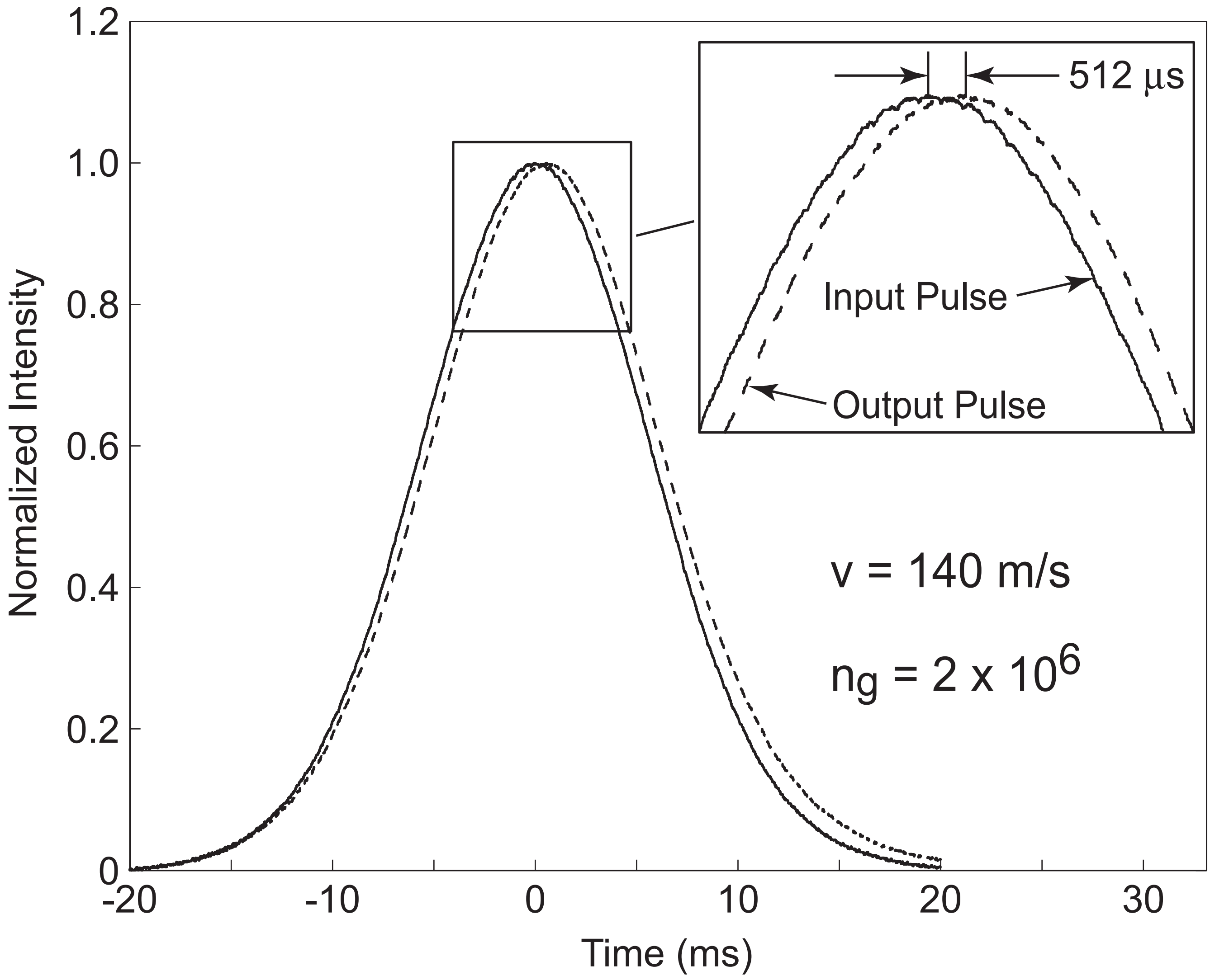
7.25-cm-long ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



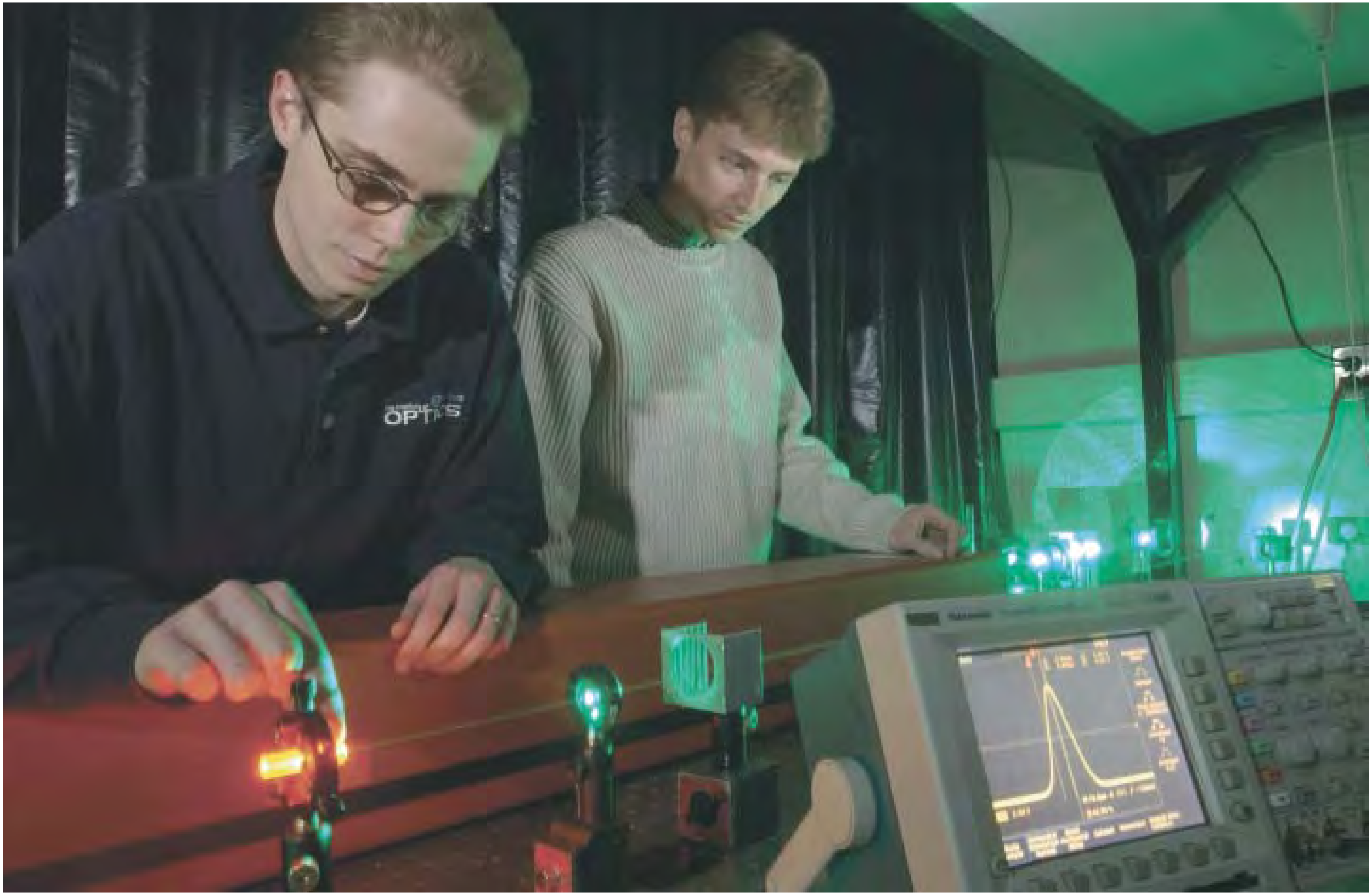
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

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

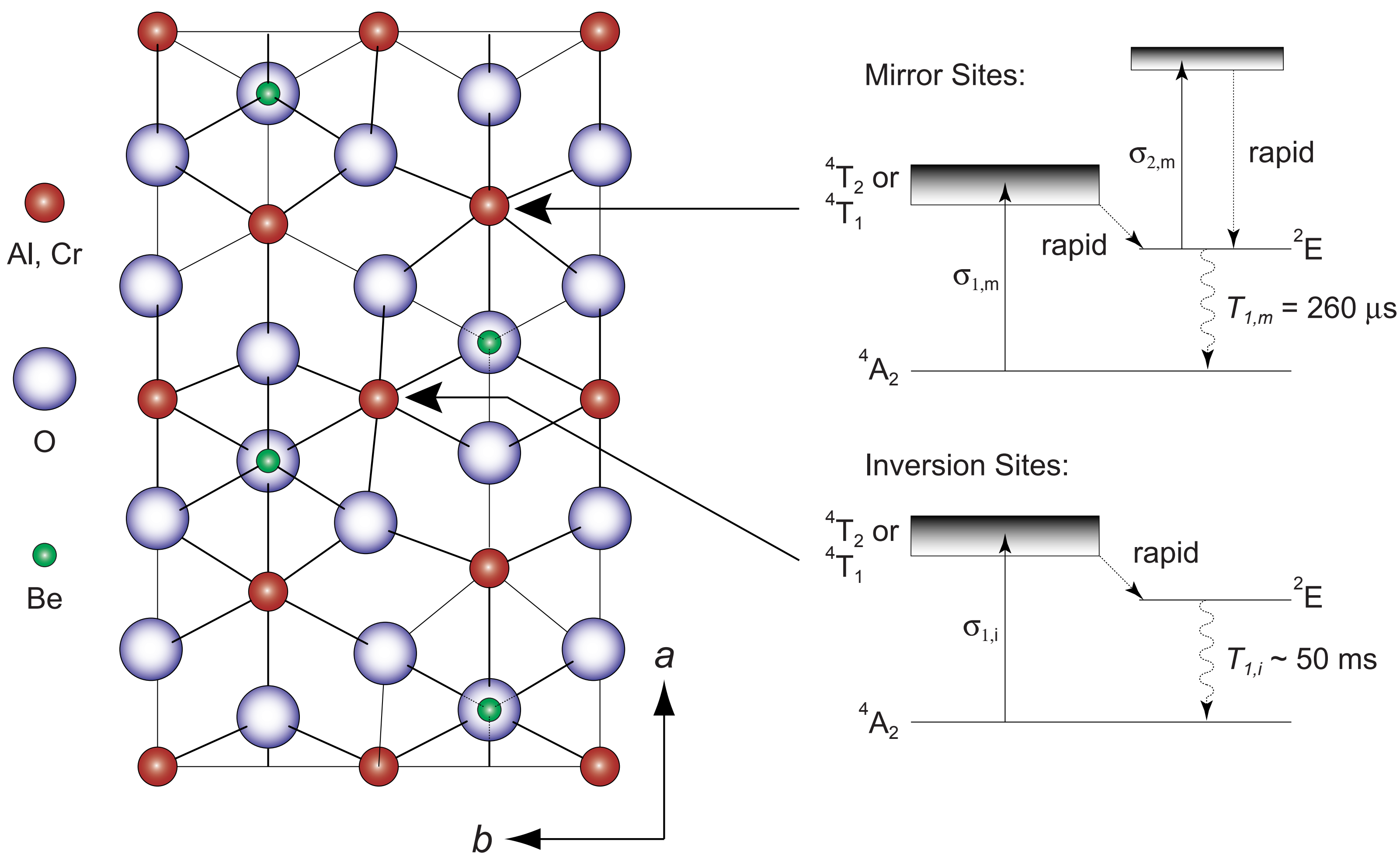
Laser need not be frequency stabilized

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

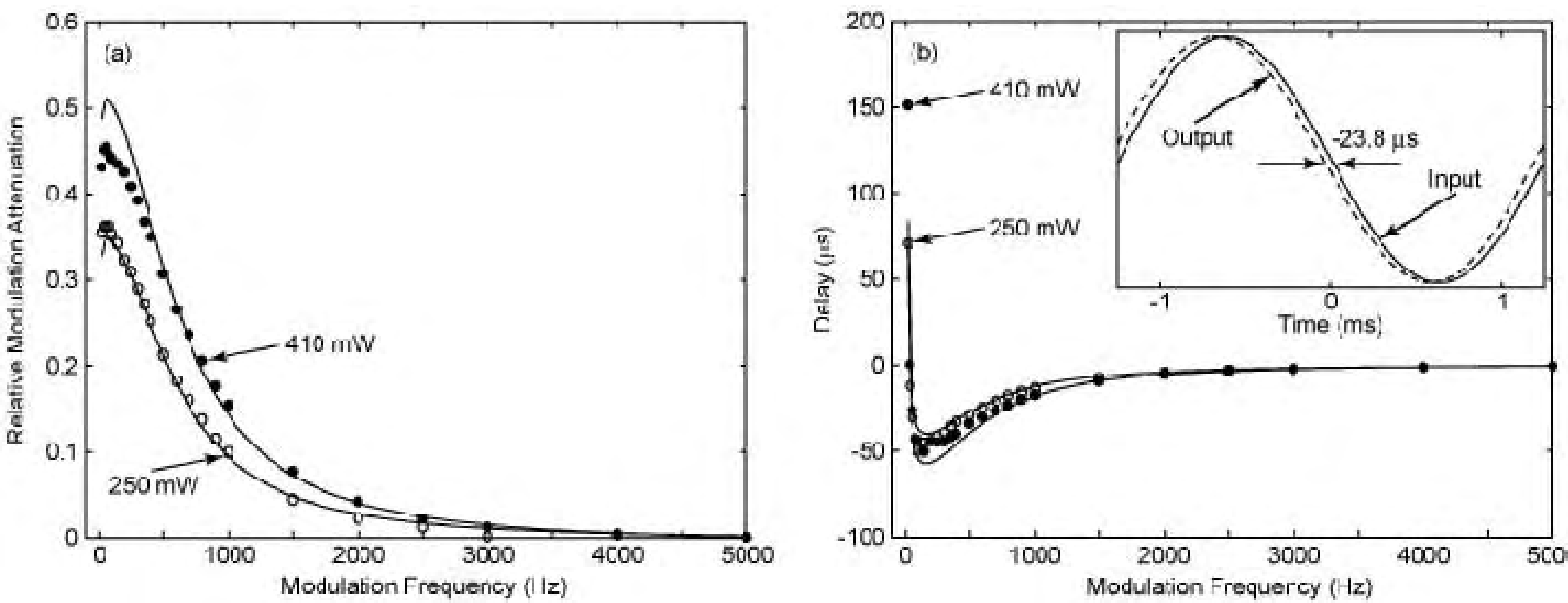


Bigelow, Lepeshkin, and Boyd, Science 301, 200 (2003).

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.

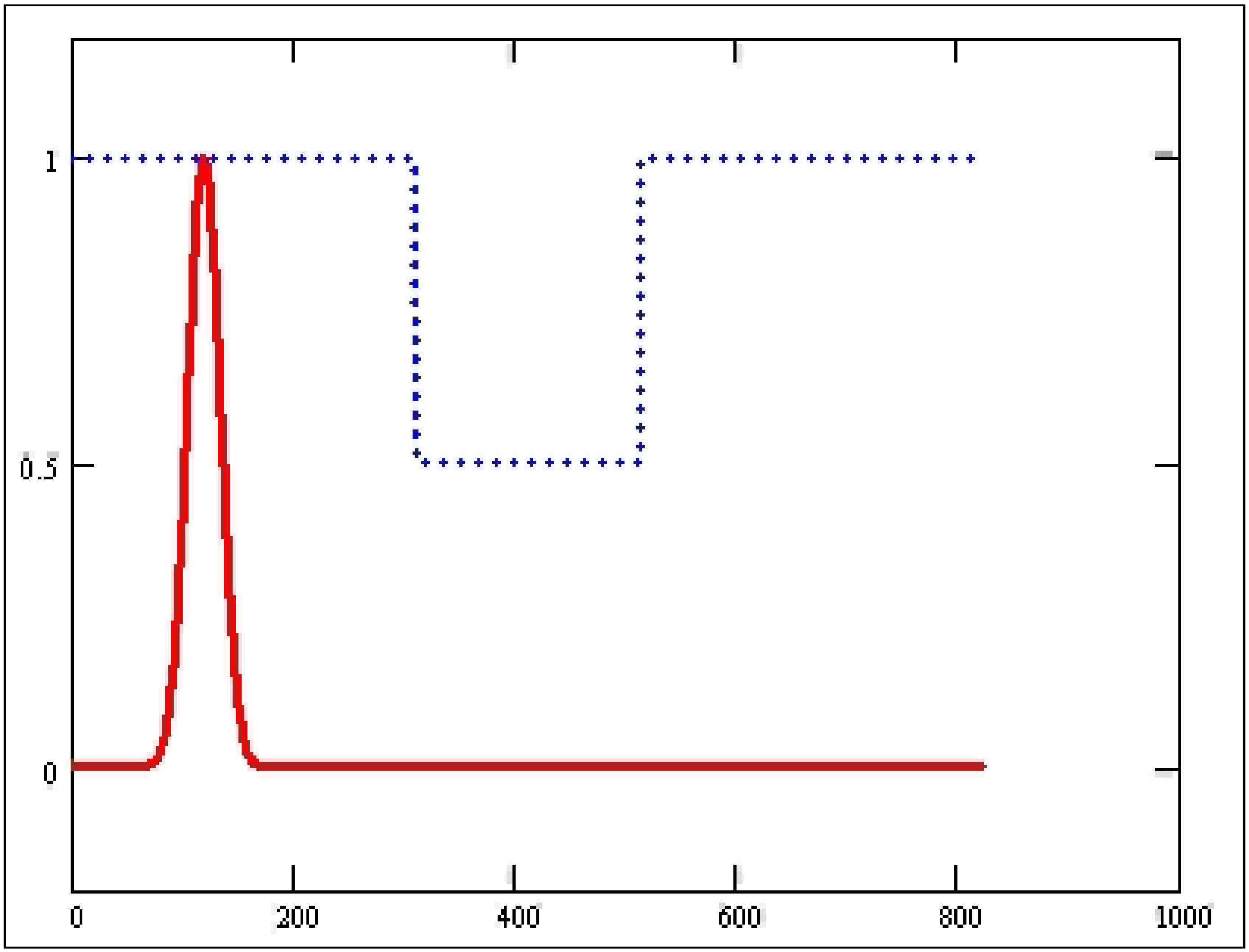
Assume an input pulse with a Gaussian temporal profile.

Study three cases:

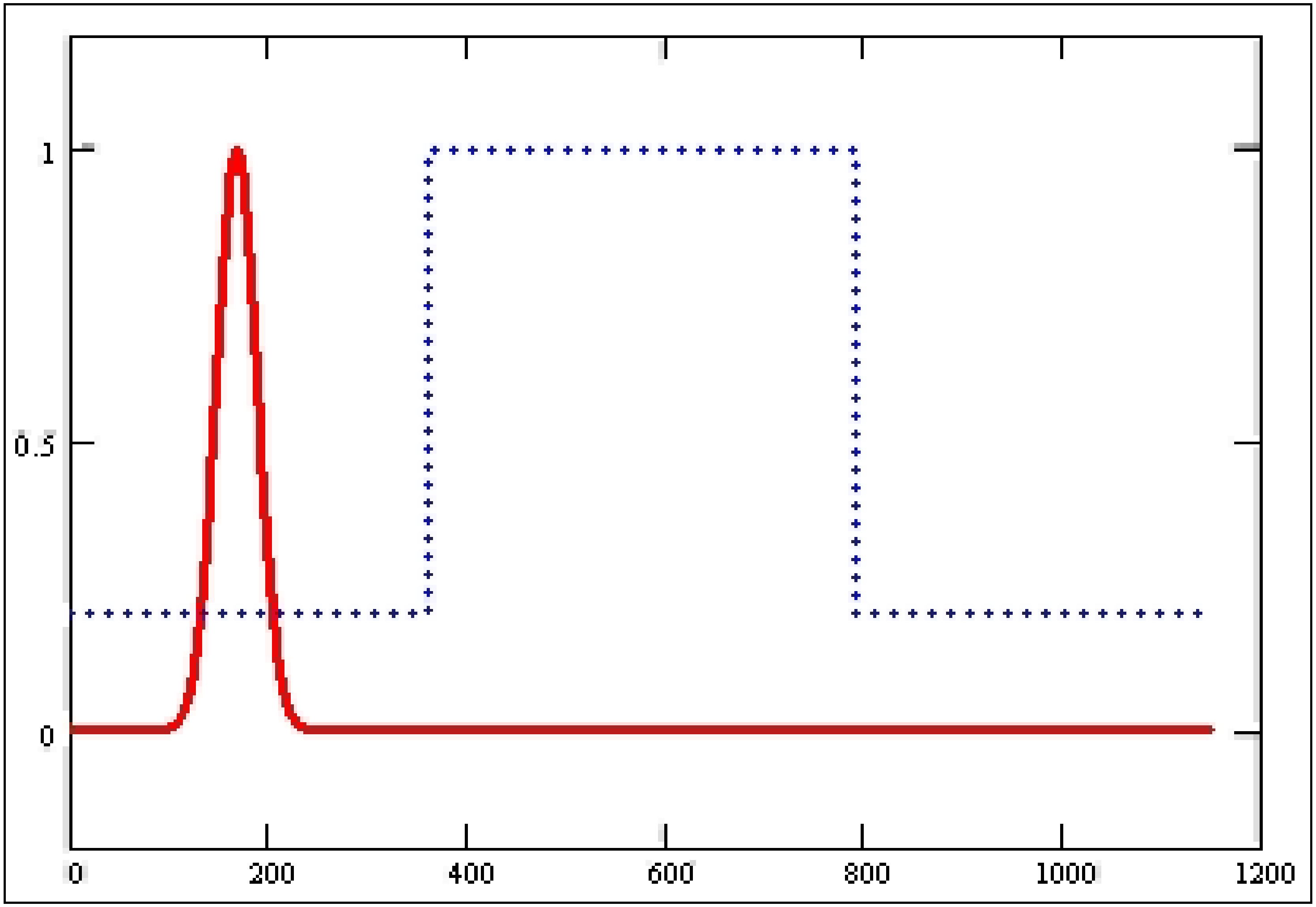
Slow light $v_g = 0.5\ c$

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

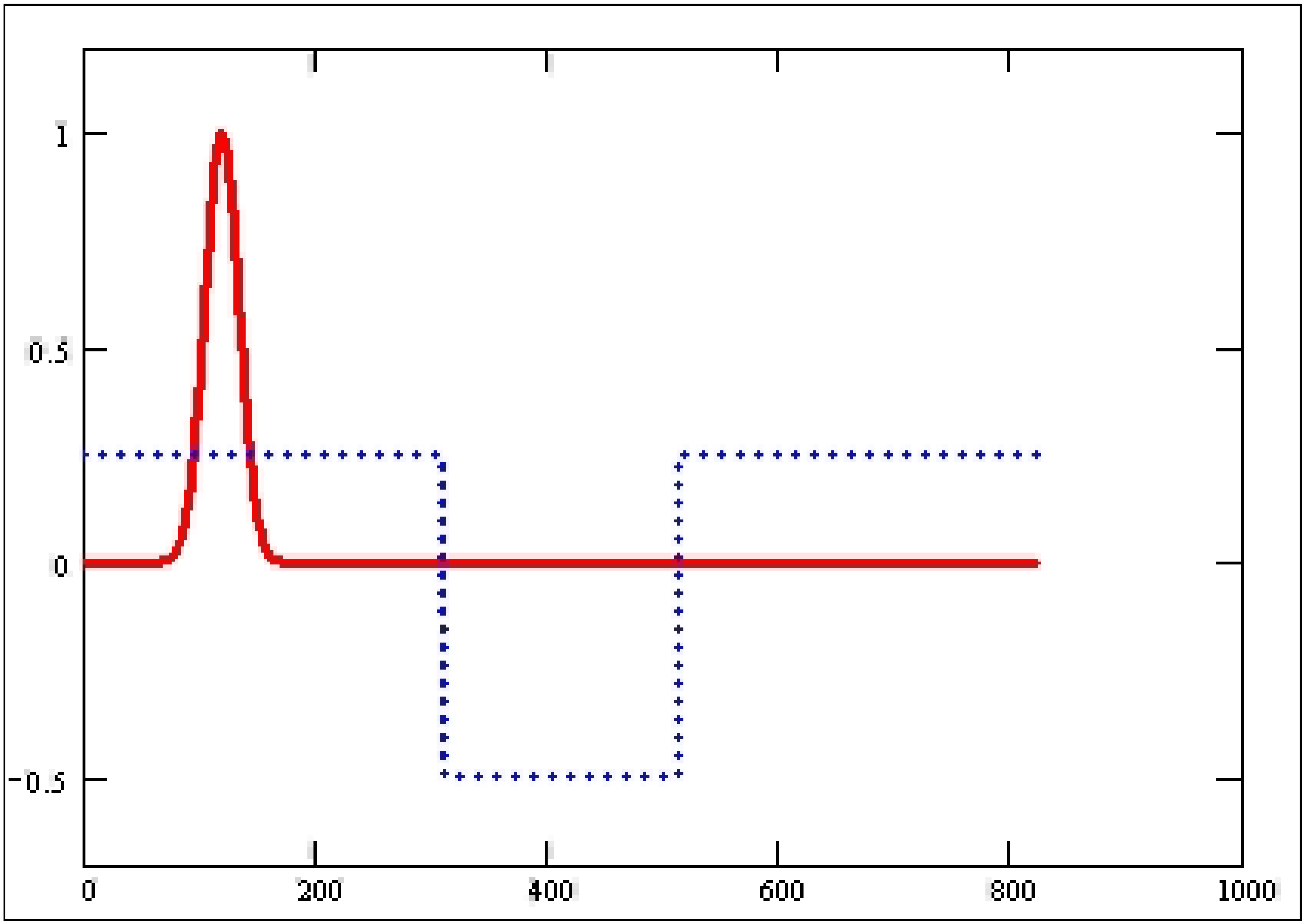
Pulse Propagation through a Slow-Light Medium ($n_g = 2$, $v_g = 0.5$ c)



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



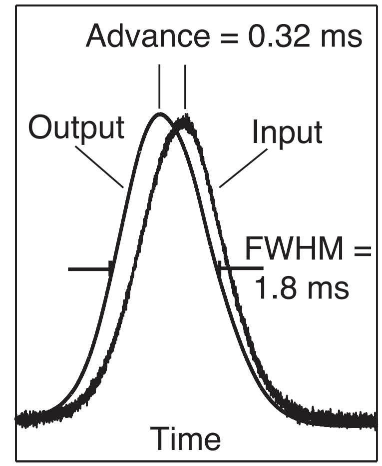
Pulse Propagation through a Fast-Light Medium (n_g = -.5, v_g = -2 c)

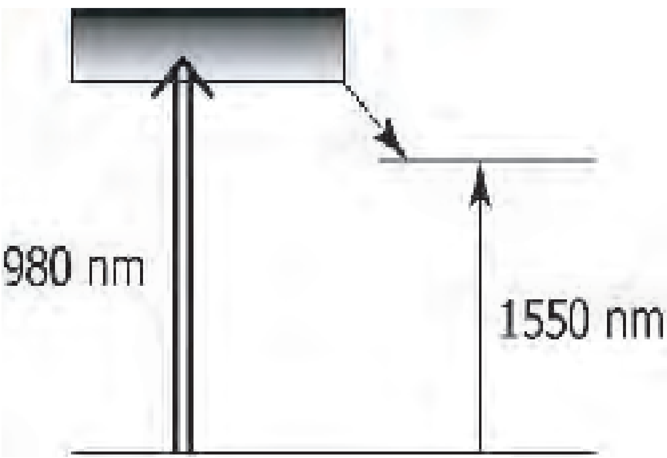


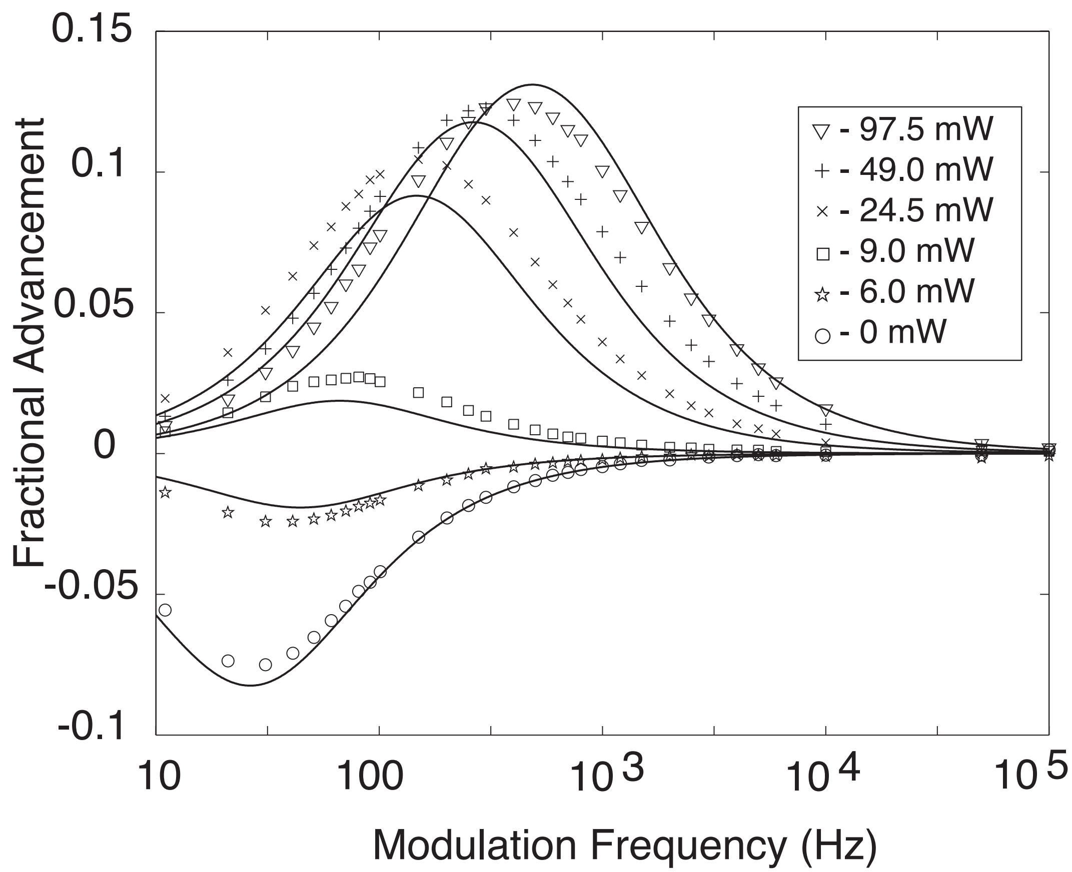
Some New Results

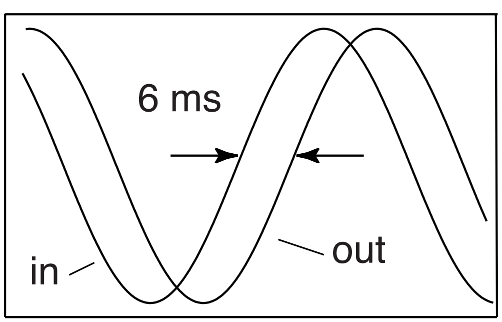
Slow and Fast Light in an Erbium Doped Fiber Amplifier

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







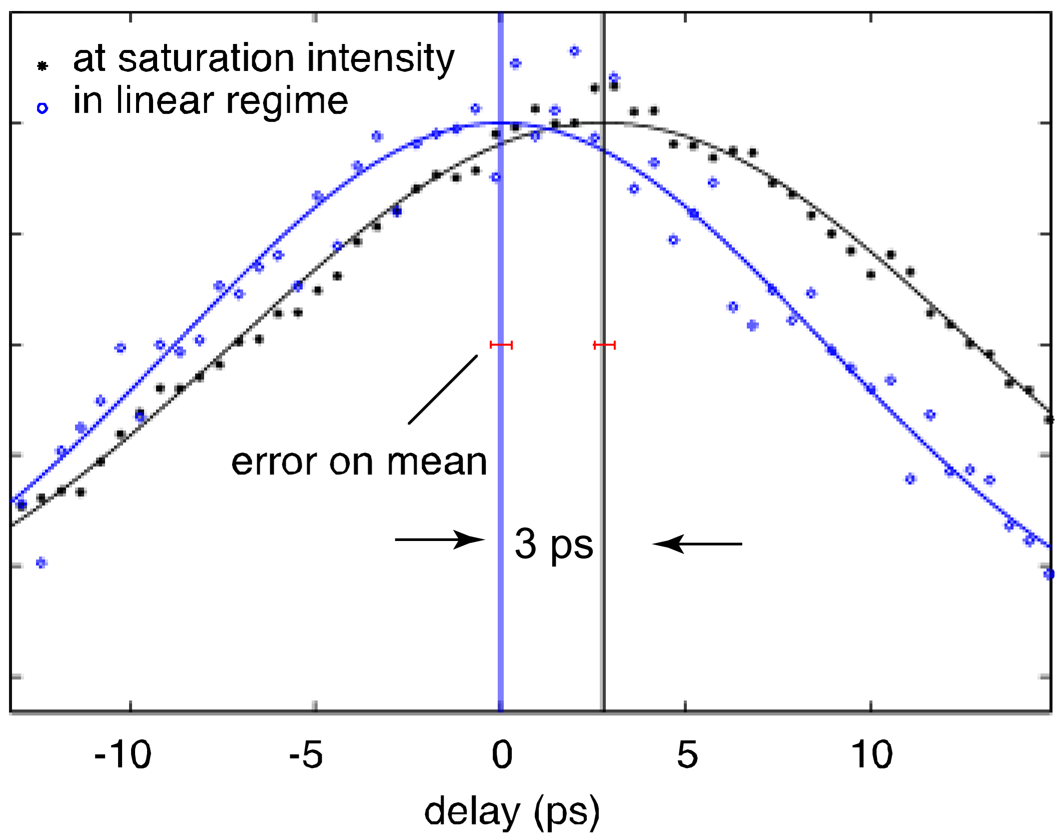


Slow Light in SC Quantum Dot Structures

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)



Limits on the Time Delay Induced by Slow-Light Propagation

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Alexander L. Gaeta
Applied and Engineering Physics, Cornell

Alan E. Willner
ECE Dept, USC

See also Phys. Rev. A 71, 023801 (2005)

Motivation: 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
$\approx$ 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?

Summary

There are no *fundamental* limitations to the maximum normalized pulse delay.

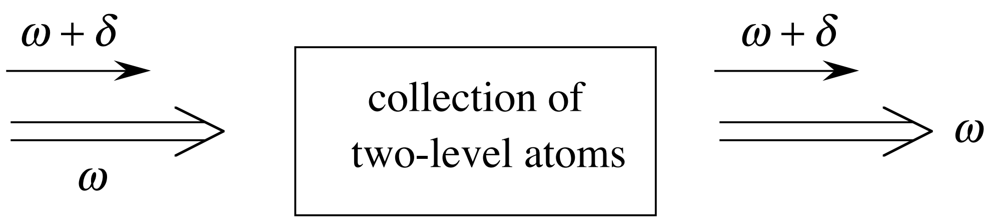
However, there are serious *practical* limitations, primarily associated with residual absorption.

To achieve a longer fractional delay saturate deeper to propagate farther

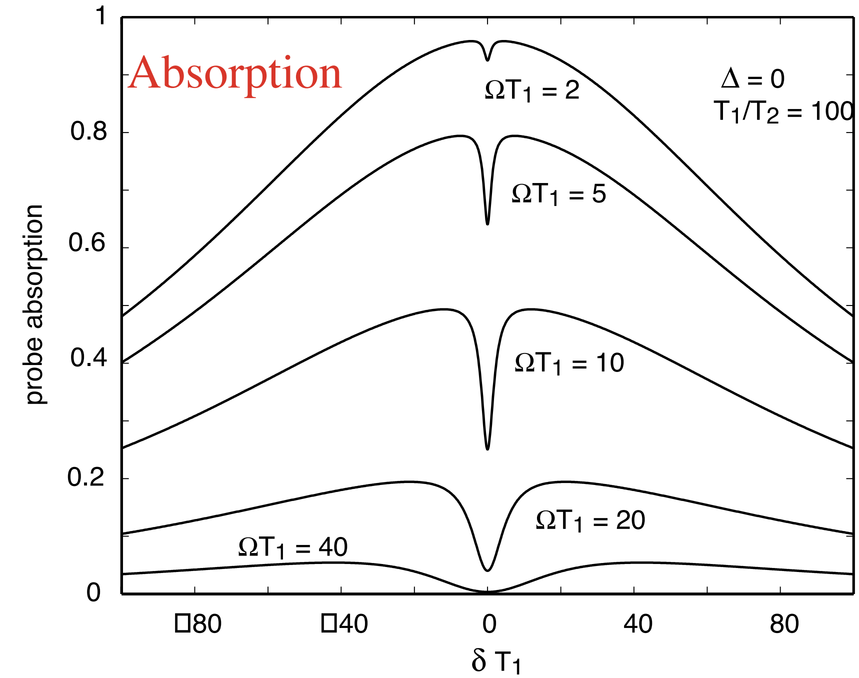
Exciting possibilities exist for optical buffering and other photonics applications if normalized time delays in the range of 10 – 1000 can be achieved.

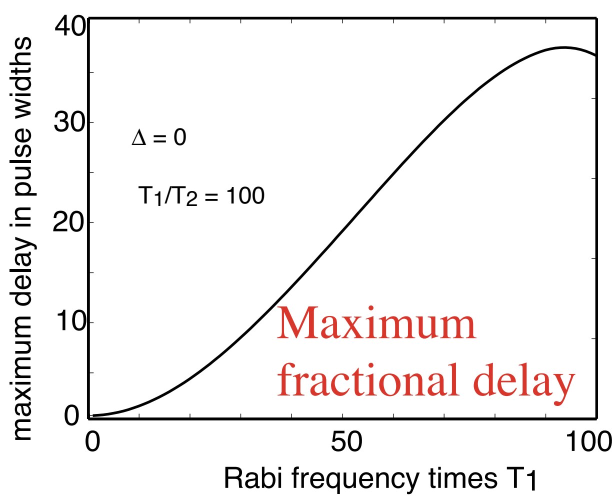
Next: Find material with faster response (semiconductors?) (to allow delay of shorter pulses)

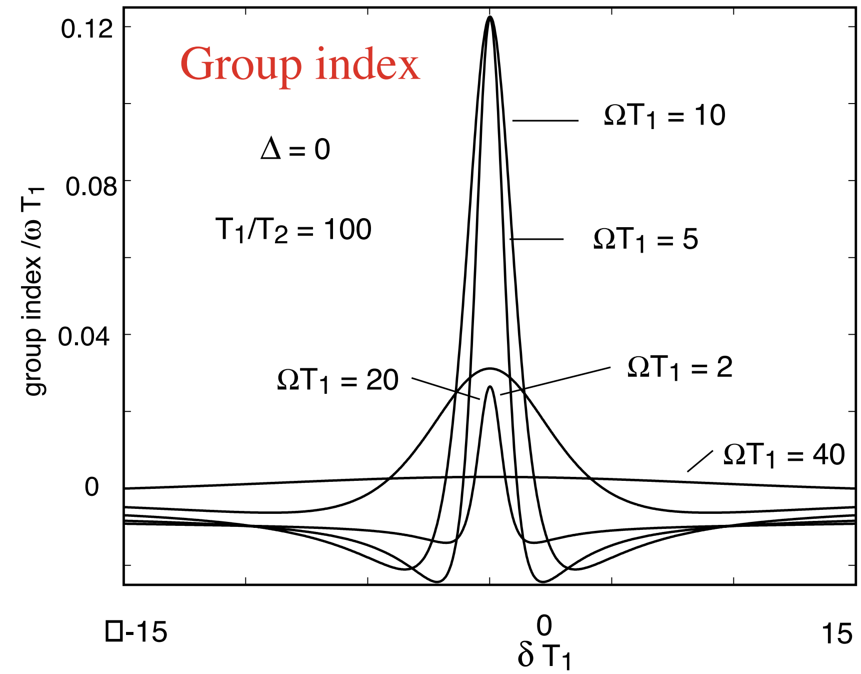
Prospects for Large Fractional Delays Using CPO



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







Boyd et al., Laser Physics 2005.

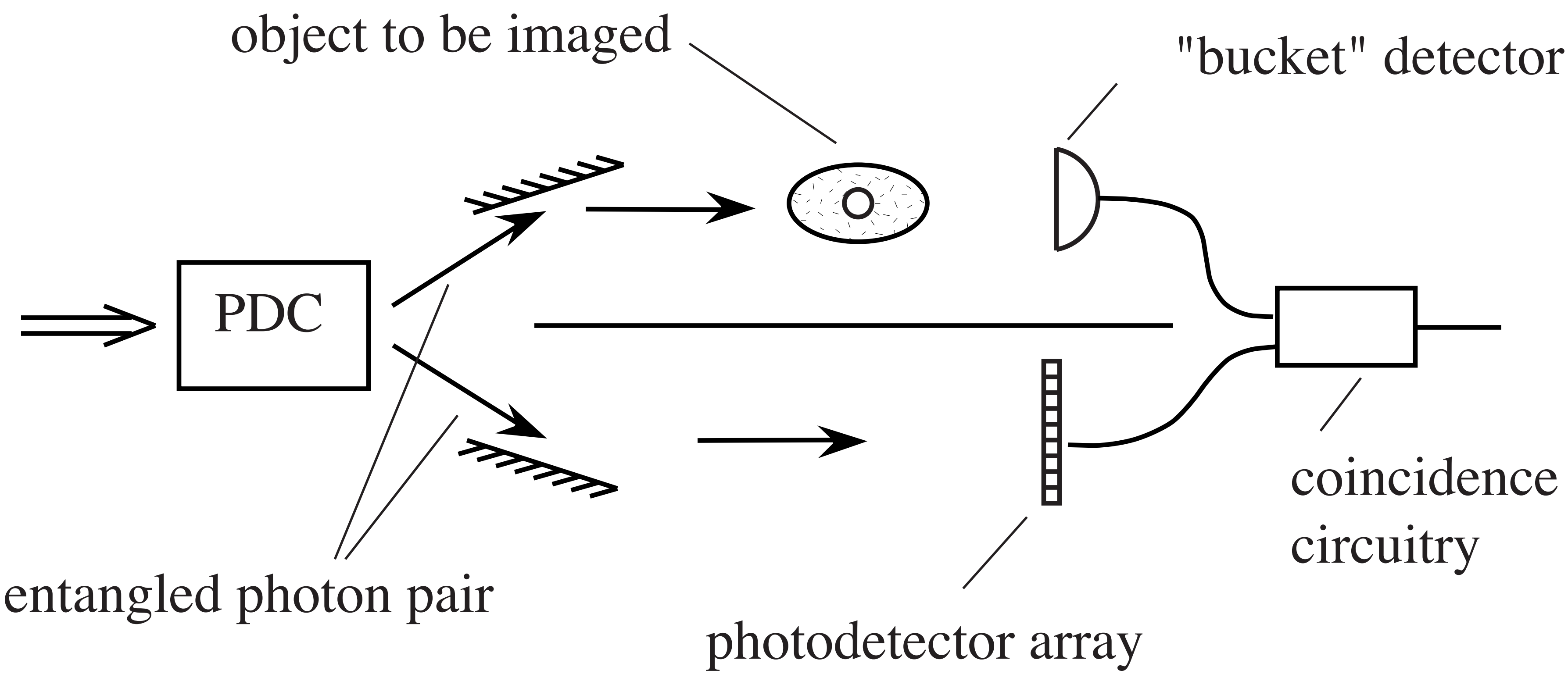
Research in Quantum Imaging

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

Robert W. Boyd, Sean J. Bentley,
Hye Jeong Chang, and Malcolm N. O’Sullivan-Hale

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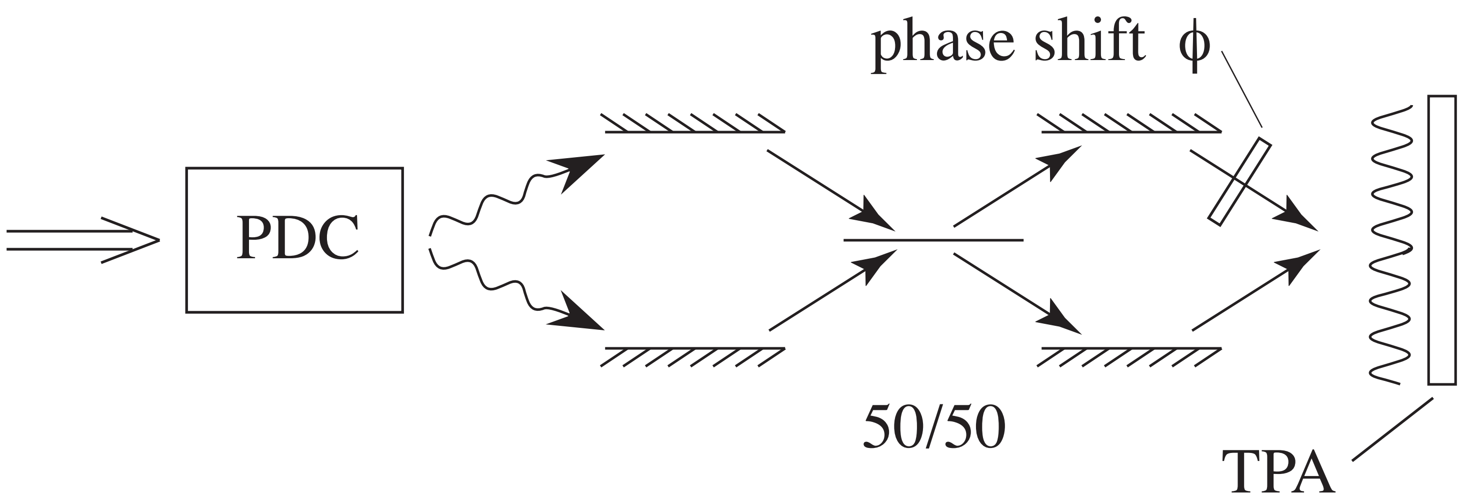
Rochester NY,USA

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?)

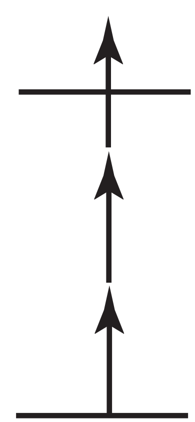
  Maybe a high-gain OPA provides the best tradeoff between high intensity and required quantum statistics

- 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 ????

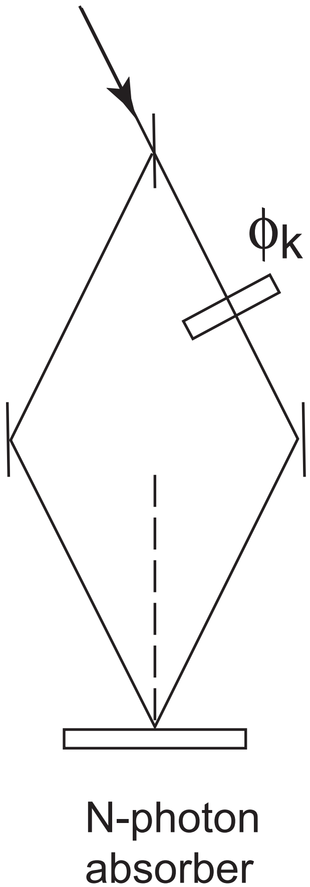
Maybe best bet is UV lithographic material excited in the visible or a broad bandgap material such as PMMA excited by multiphoton absorption.

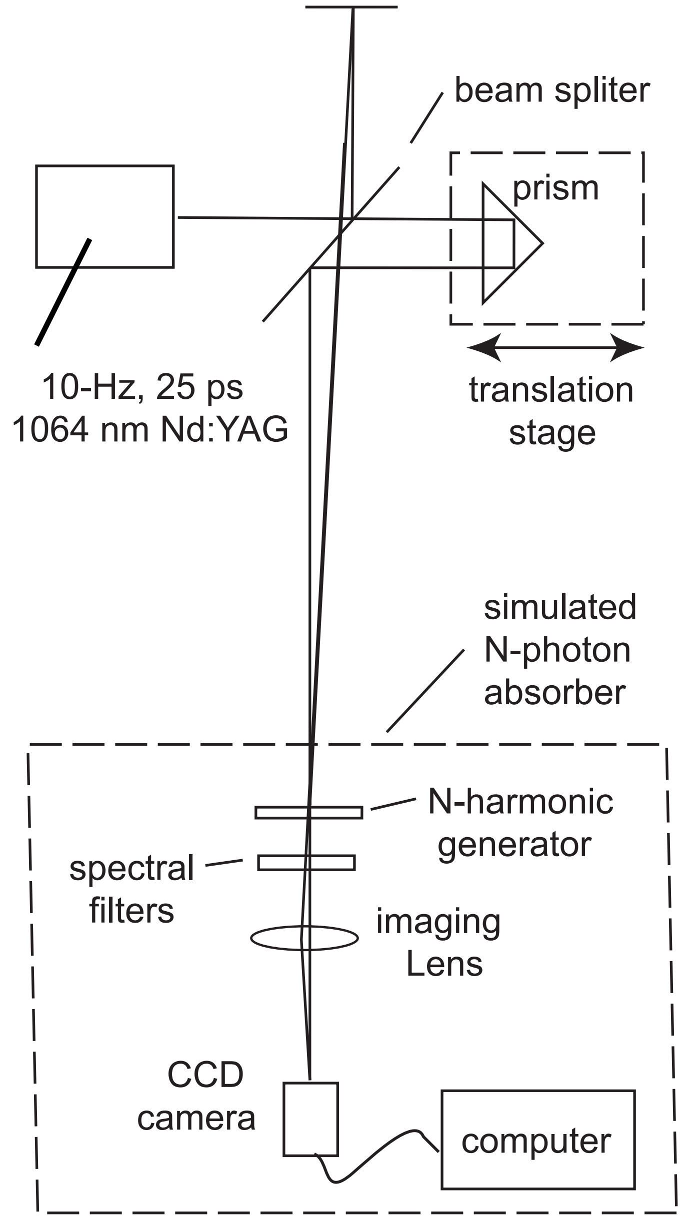


3PA in PMMA breaks chemical bond, modifying optical properties.

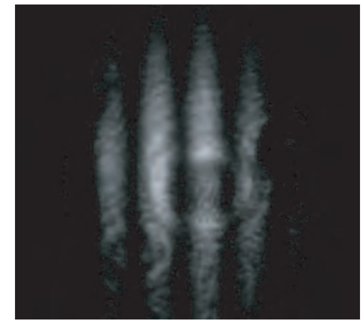
Non-Quantum Quantum Lithography

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

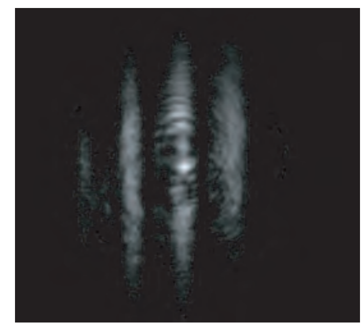




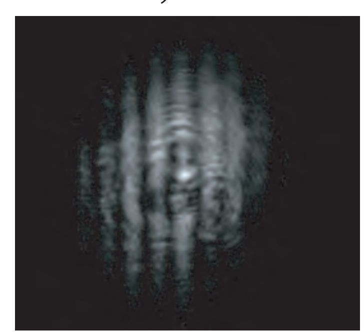
N=1, M=1



N=2, M=1

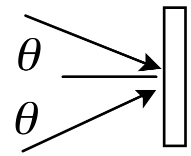


N=2, M=2



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**

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

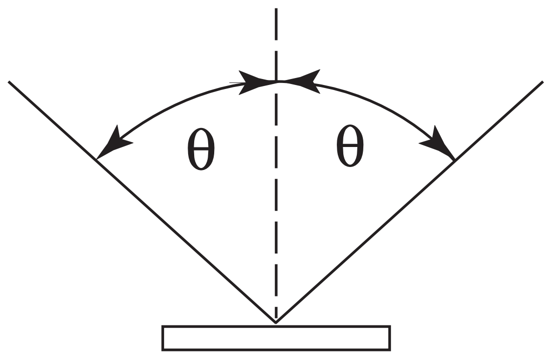
$$= 3/2 + 2 \cos kx + (1/2) \cos 2kx$$

- **Two-photon absorbing medium, entangled photons**

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

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

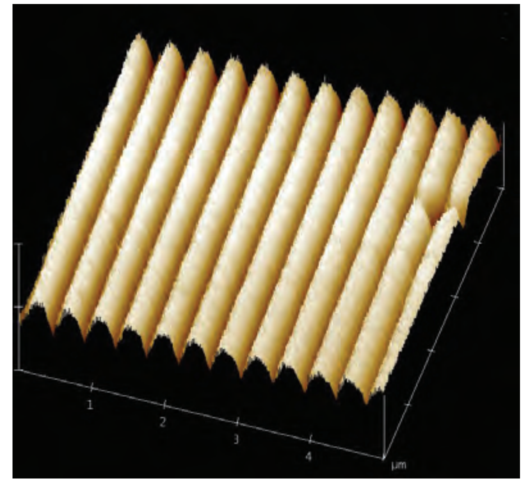
Demonstration of Fringes Written into PMMA



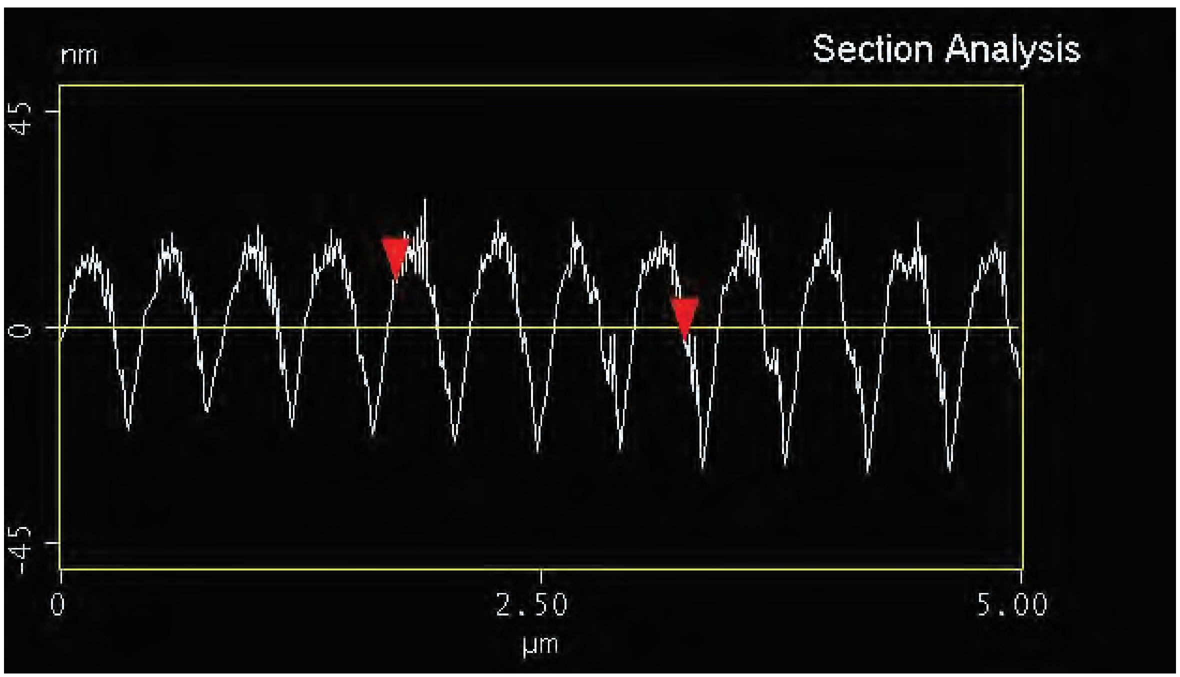
N-photon absorber
(N = 3 ?)

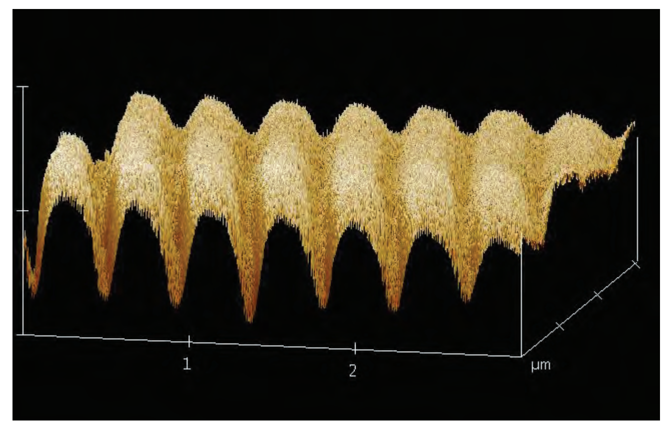
θ = 70 degrees
write wavelength = 800 nm
pulse energy = 130 μJ per beam
pulse duration = 120 fs
period = $\lambda / (2 \sin \theta)$ = 425 nm

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



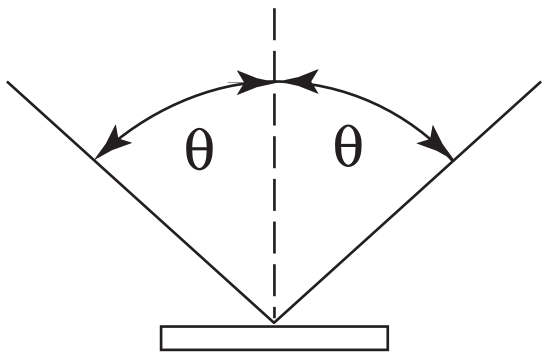
AFM





PMMA is a standard
lithographic material

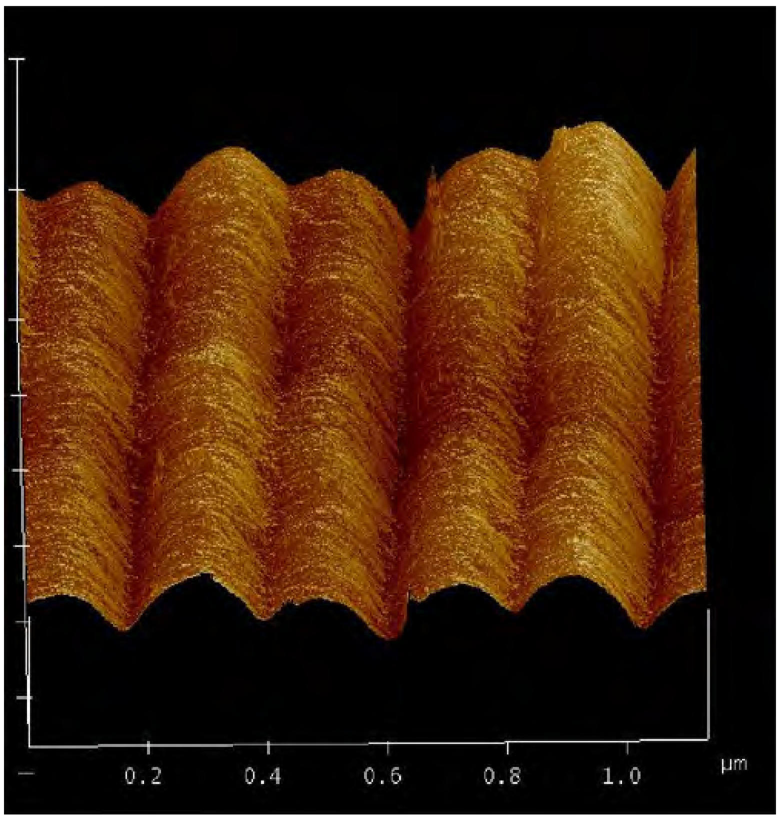
Demonstration of Sub-Rayleigh Fringes (Period = λ/4)

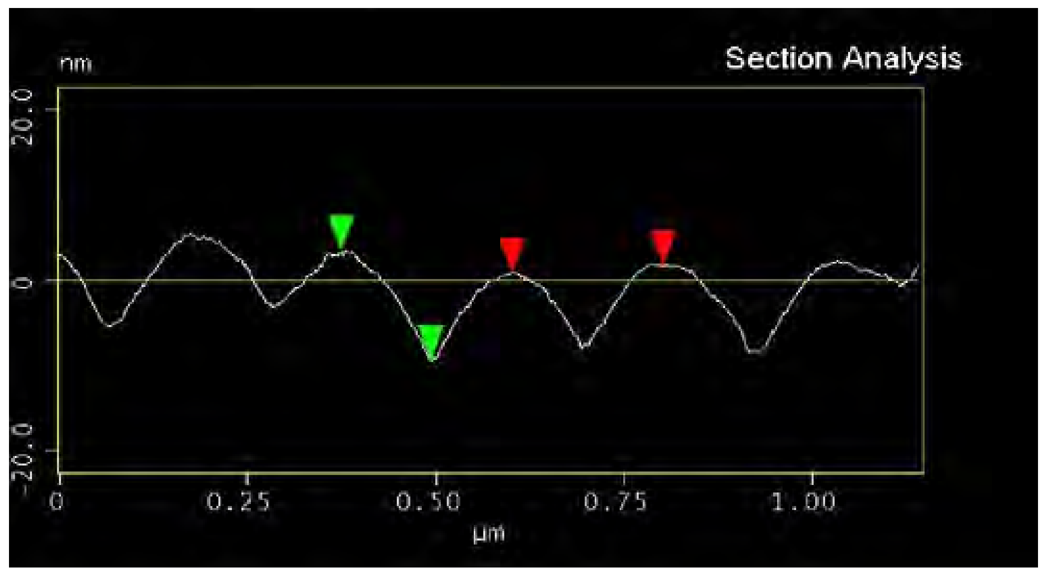


N-photon absorber

θ = 70 degrees
two pulses with 180 deg phase shift
write wavelength = 800 nm
pulse energy = 90 μJ per beam
fundamental period = λ / (2 sin θ) = 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

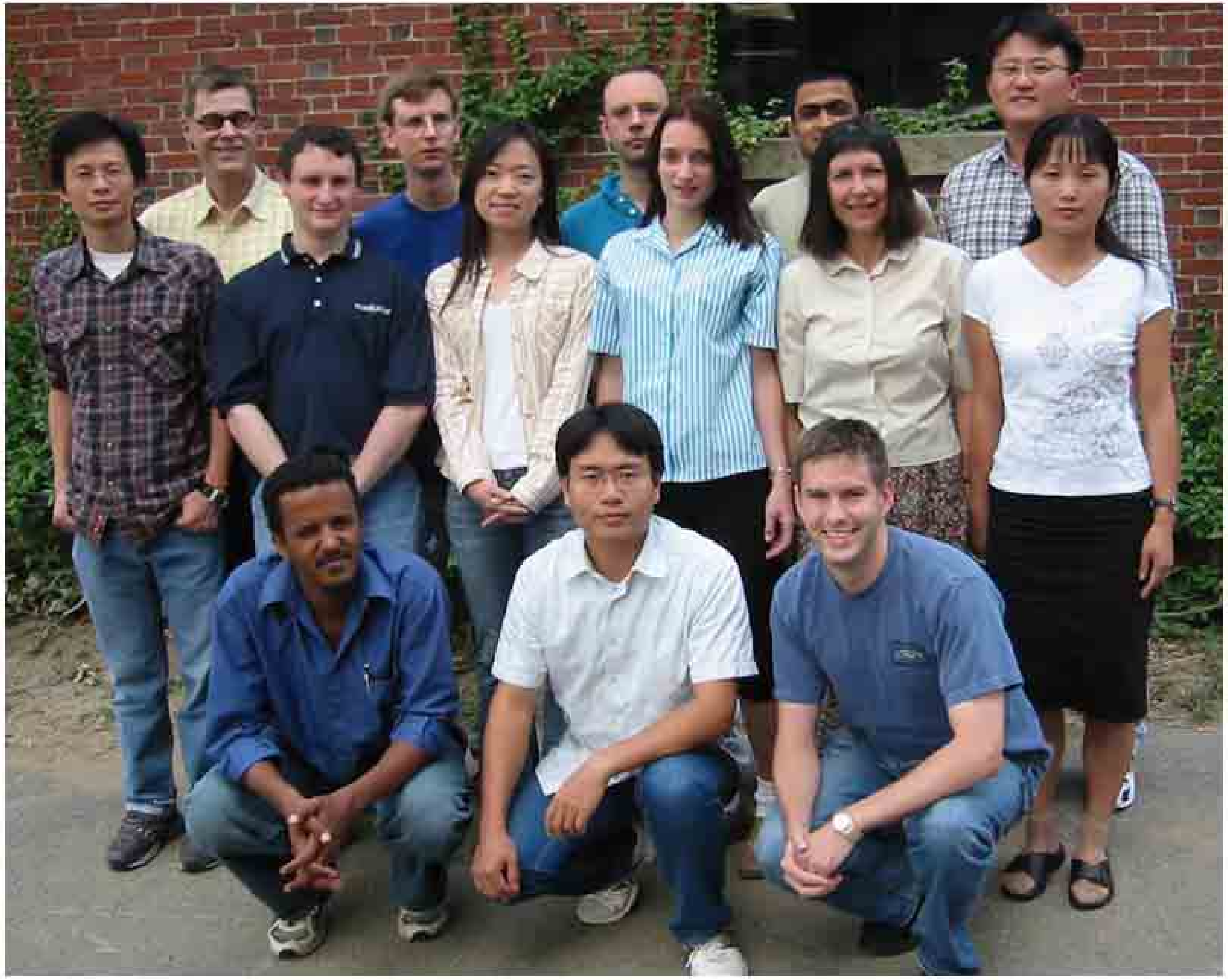
- Demonstrates an N-photon absorber with adequate resolution to be of use in true quantum lithography

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