# Superluminal and Ultra-Slow Light Propagation in Room Temperature Solids
# and
# Quantum (and non-Quantum) Imaging
# and
# Artificial Material for Nonlinear Optics

**Robert W. Boyd**

The Institute of Optics and
Department of Physics and Astronomy
University of Rochester, Rochester, NY  14627
http://www.optics.rochester.edu

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Boyd

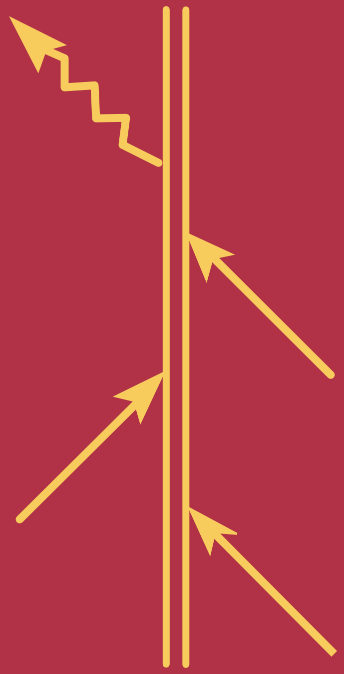
NONLINEAR OPTICS

SECOND
EDITION

ACADEMIC
PRESS

# NONLINEAR OPTICS

## SECOND EDITION



### Robert W. Boyd

# Interest in Slow Light

Fundamentals of optical physics

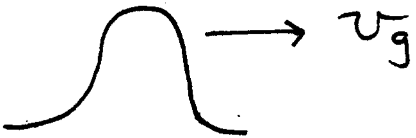
Intrigue: Can (group) refractive index really be $10^6$?

Optical delay lines, optical storage, optical memories

Implications for quantum information

# 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!

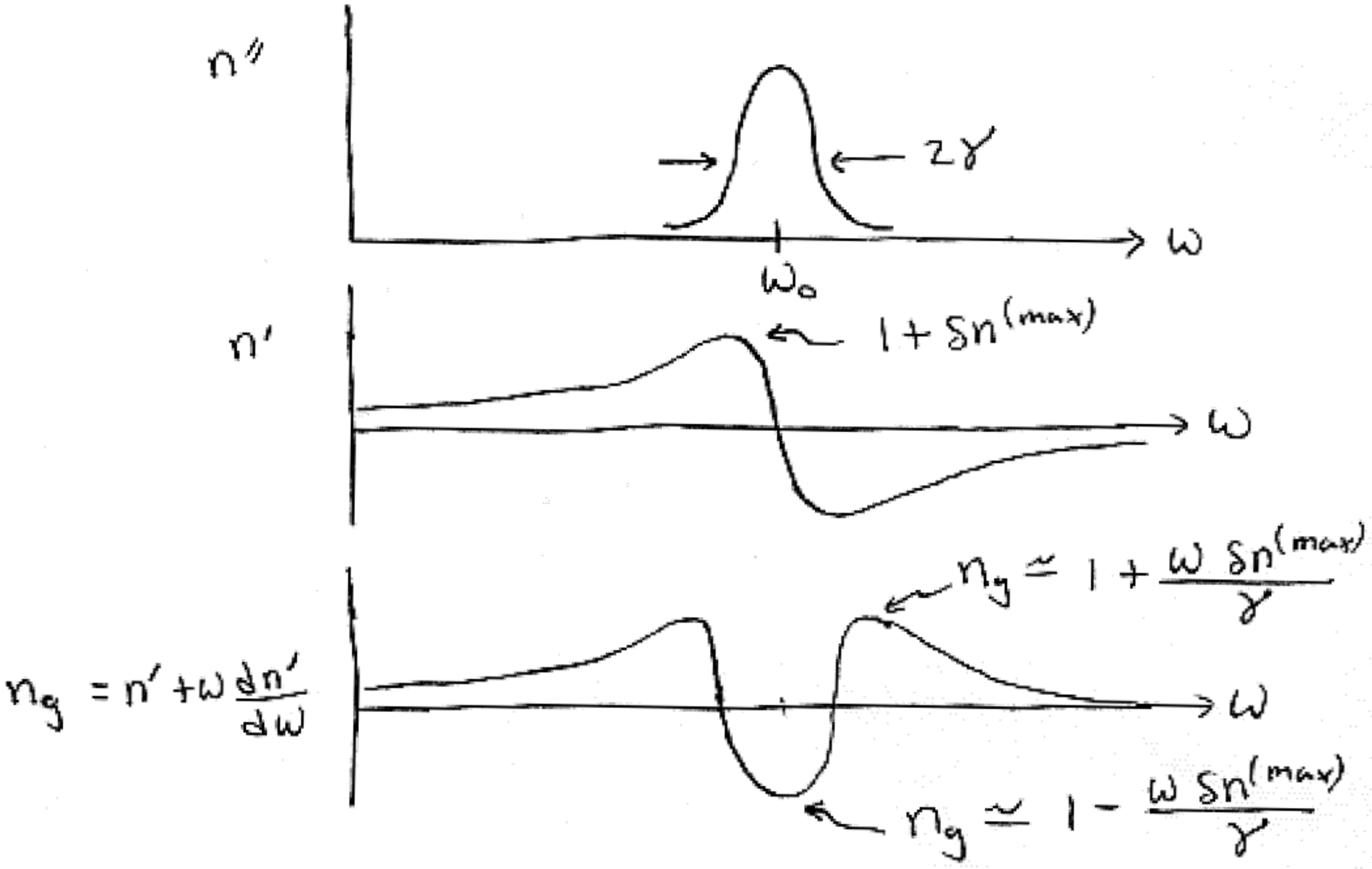
# Light Propagation in Atomic Vapors

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

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

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

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



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

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

(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 $\gamma$
(produce sub-Doppler linewidth)

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

# Slow Light in Atomic Media

Slow light propagation in atomic media (vapors and BEC), facilitated by quantum coherence effects, has been successfully observed by many groups.

# Challenge/Goal

Slow light in room-temperature solid-state material.

- Slow light in room temperature ruby
  (facilitated by a novel quantum coherence effect)
- Slow light in a structured waveguide

# Slow Light in Ruby

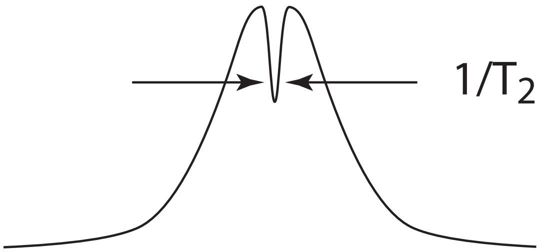
Need a large dn/dω. (How?)

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

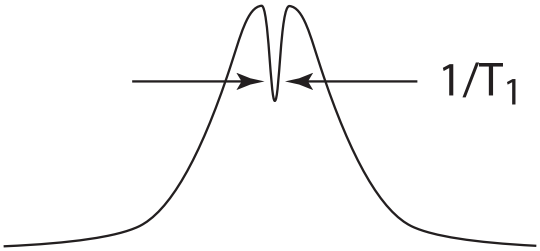
Well-known (to the few people how know it well) how to do so:

Make use of "spectral holes" due to population oscillations.

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



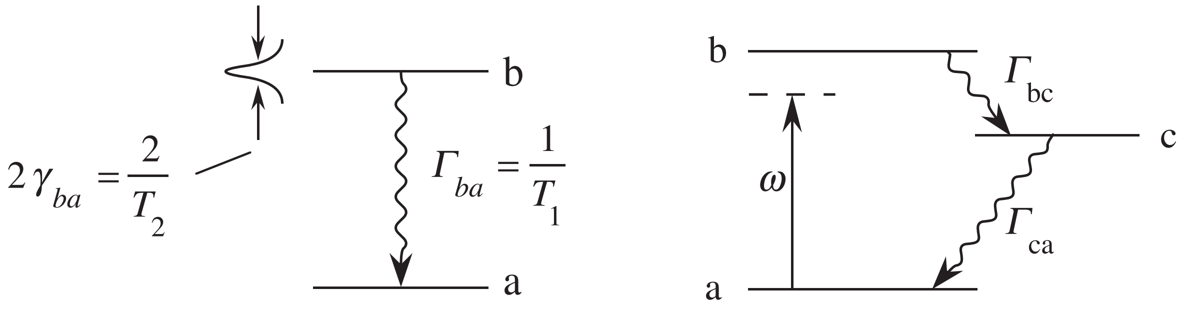
inhomogeneously
broadened medium

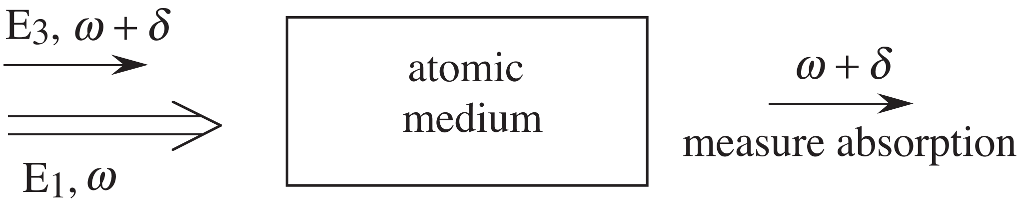


homogeneously
broadened medium
(or inhomogeneously
broadened)

PRL 90,113903(2003); see also news story in Nature.

# Spectral Holes Due to Population Oscillations




$E_3, \omega + \delta$

$E_1, \omega$

atomic
medium

$\omega + \delta$

measure absorption

Population inversion:

$$(\rho_{bb} - \rho_{aa}) = w \qquad w(t) \approx w^{(0)} + w^{(-\delta)} e^{i\delta t} + w^{(\delta)} e^{-i\delta t}$$

population oscillation terms important only for $\delta \leq 1/T_1$

Probe-beam response:

$$\rho_{ba}(\omega + \delta) = \frac{\mu_{ba}}{\hbar} \frac{1}{\omega - \omega_{ba} + i/T_2} \left[ E_3 w^{(0)} + E_1 w^{(\delta)} \right]$$

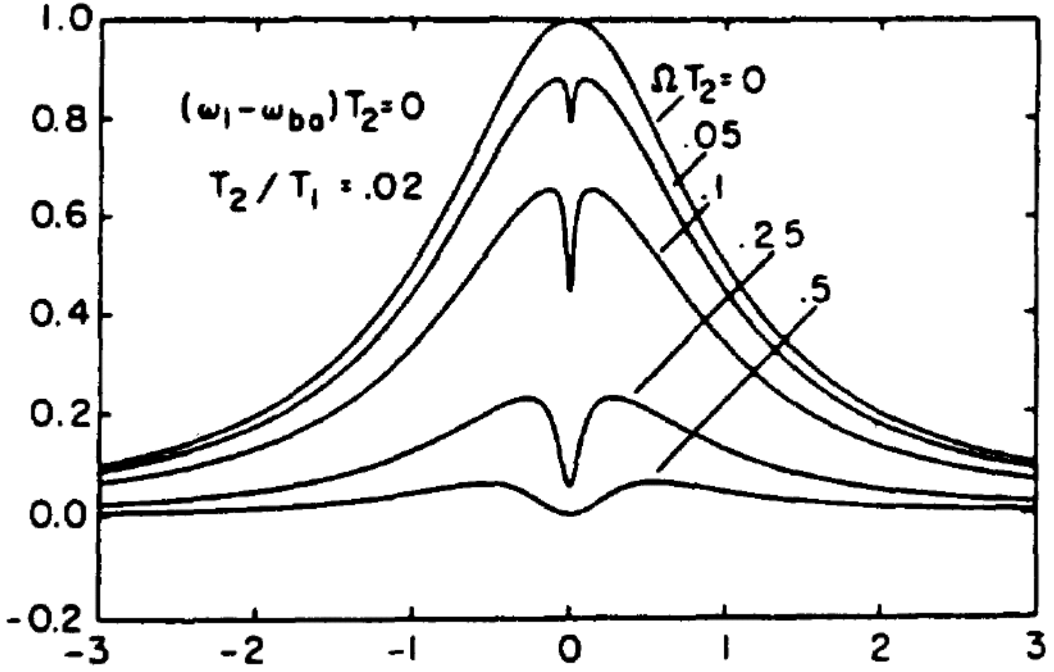
Probe-beam absorption:

$$\alpha(\omega + \delta) \propto \left[ w^{(0)} - \frac{\Omega^2 T_2}{T_1} \frac{1}{\delta^2 + \beta^2} \right]$$

linewidth $\quad \beta = (1/T_1)(1 + \Omega^2 T_1 T_2)$

# Spectral Holes in Homogeneously Broadened Materials

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

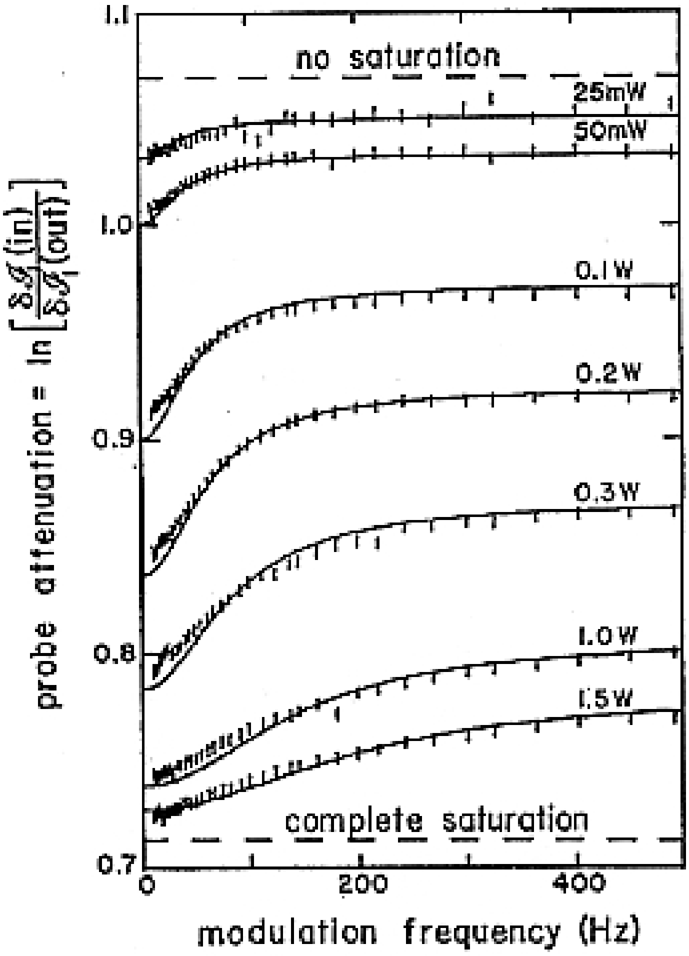


Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

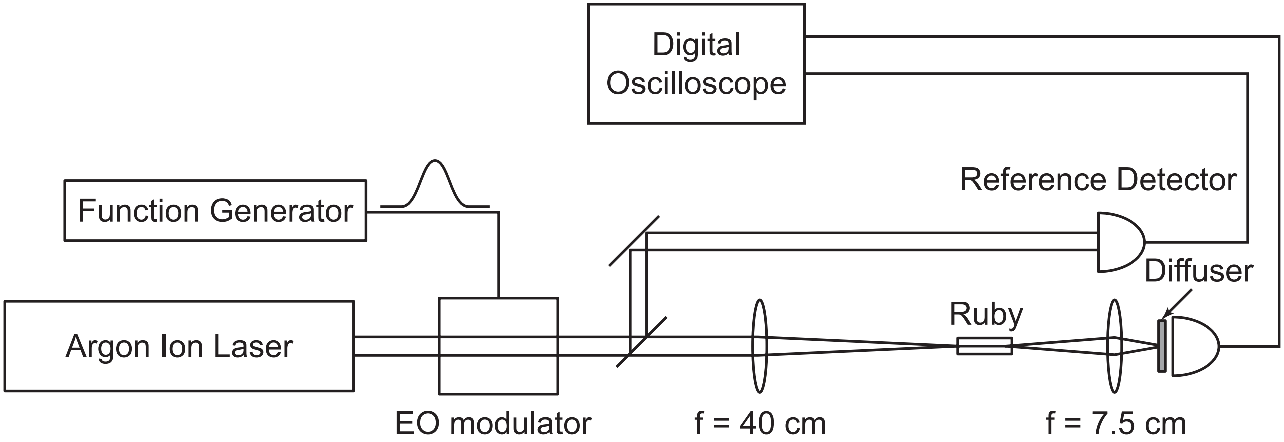
Volume 45, number 6 OPTICS COMMUNICATIONS 15 May 1983

# OBSERVATION OF A SPECTRAL HOLE DUE TO POPULATION OSCILLATIONS IN A HOMOGENEOUSLY BROADENED OPTICAL ABSORPTION LINE

Lloyd W. HILLMAN, Robert W. BOYD, Jerzy KRASINSKI and C.R. STROUD, Jr.
*The Institute of Optics, University of Rochester, Rochester, NY 14627, USA*

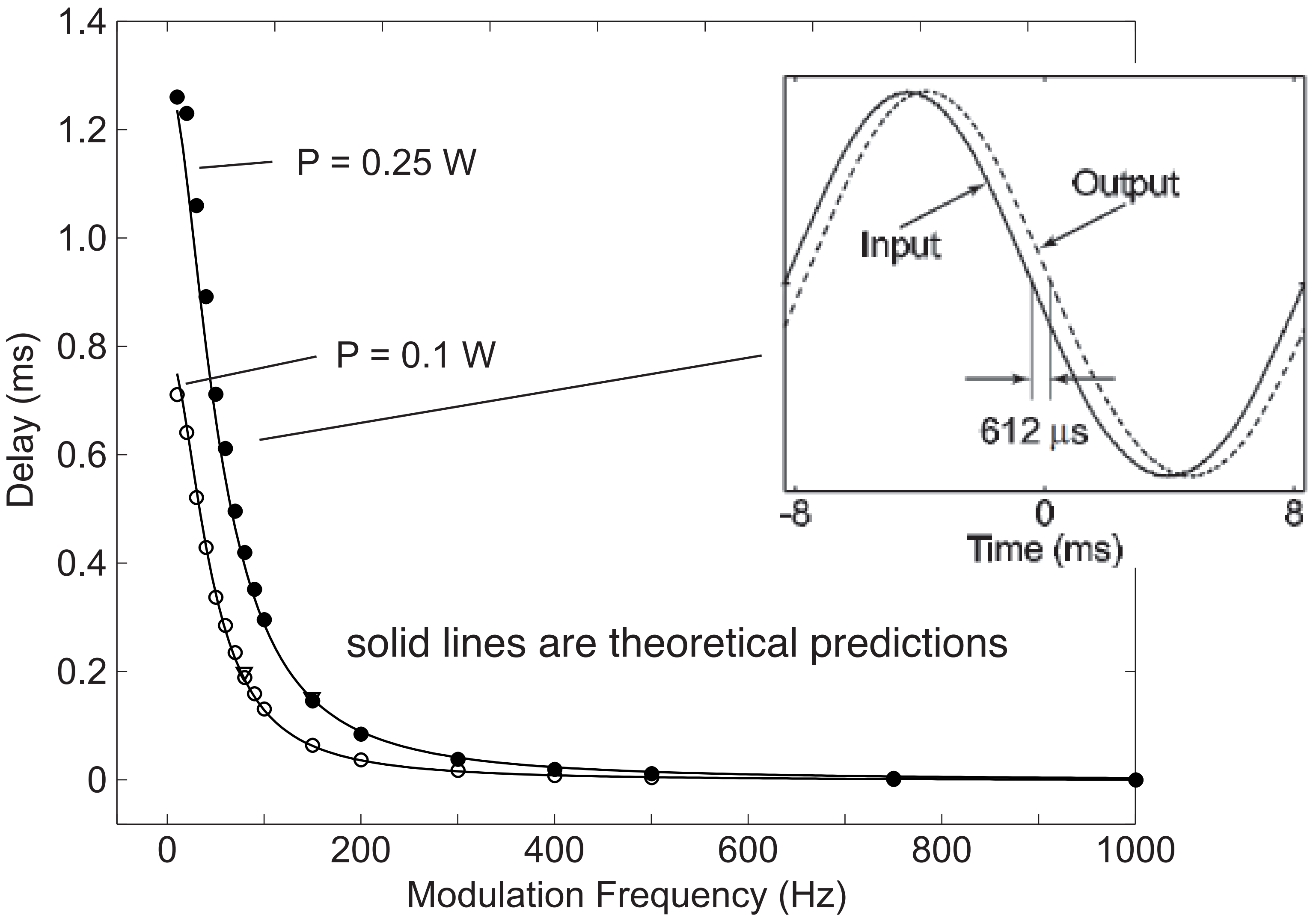


# Experimental Setup Used to Observe Slow Light in Ruby



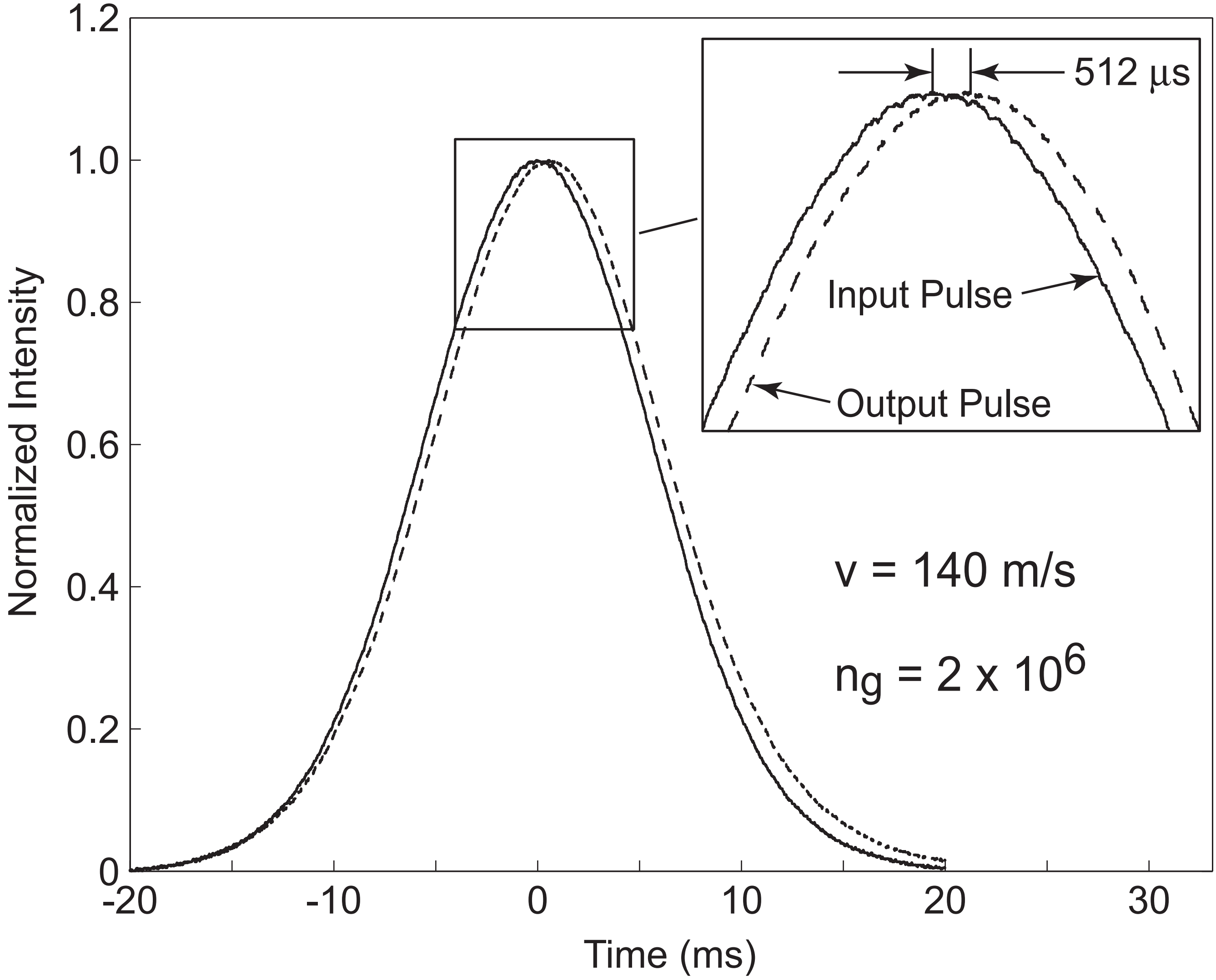
7.25 cm ruby laser rod (pink ruby)

# Measurement of Delay Time for Harmonic Modulation



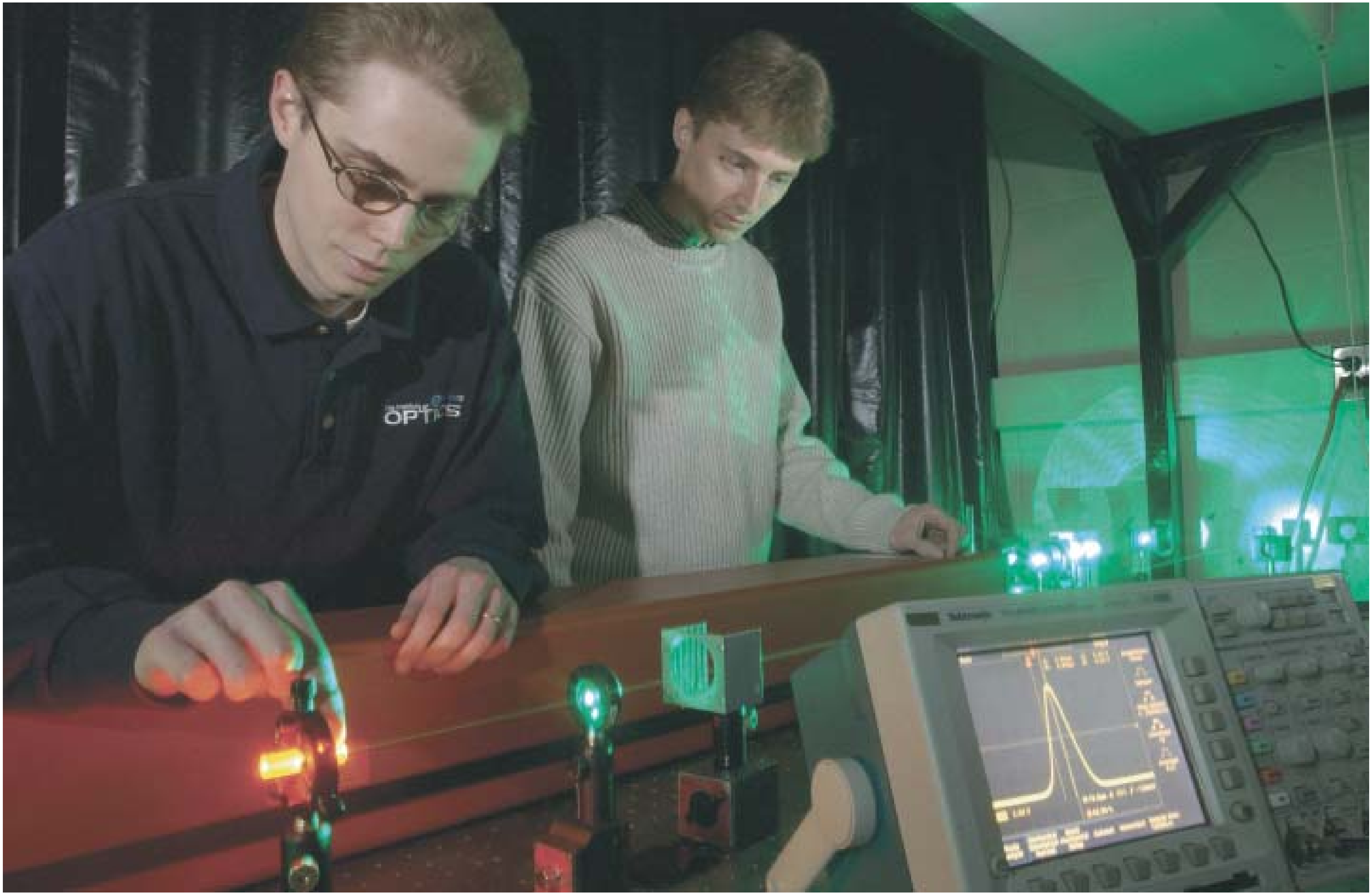
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

# Gaussian Pulse Propagation Through Ruby

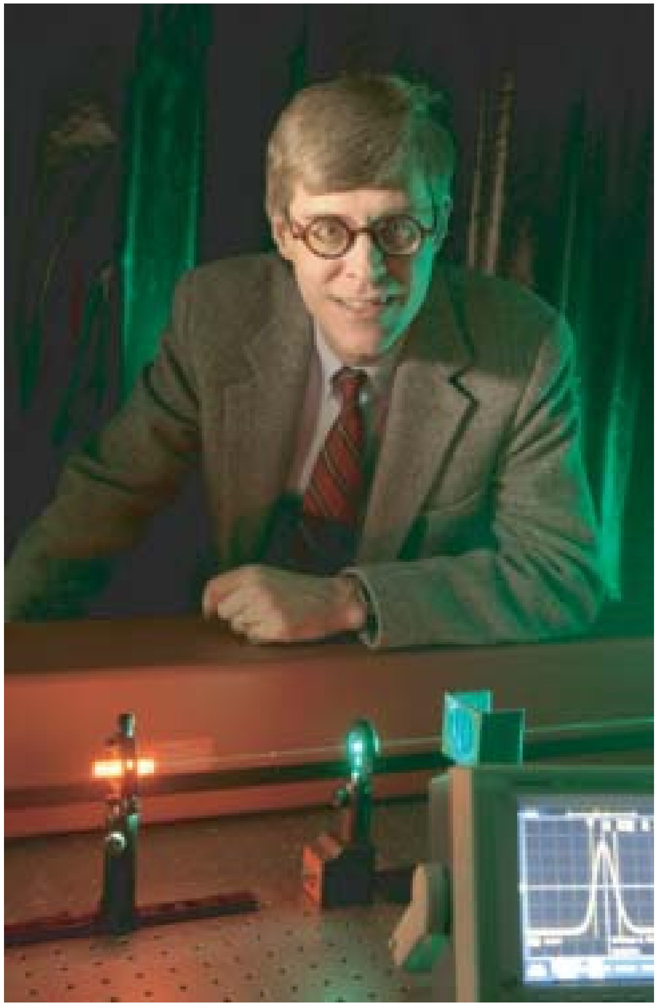


No pulse distortion!

# Matt Bigelow and Nick Lepeshkin in the Lab



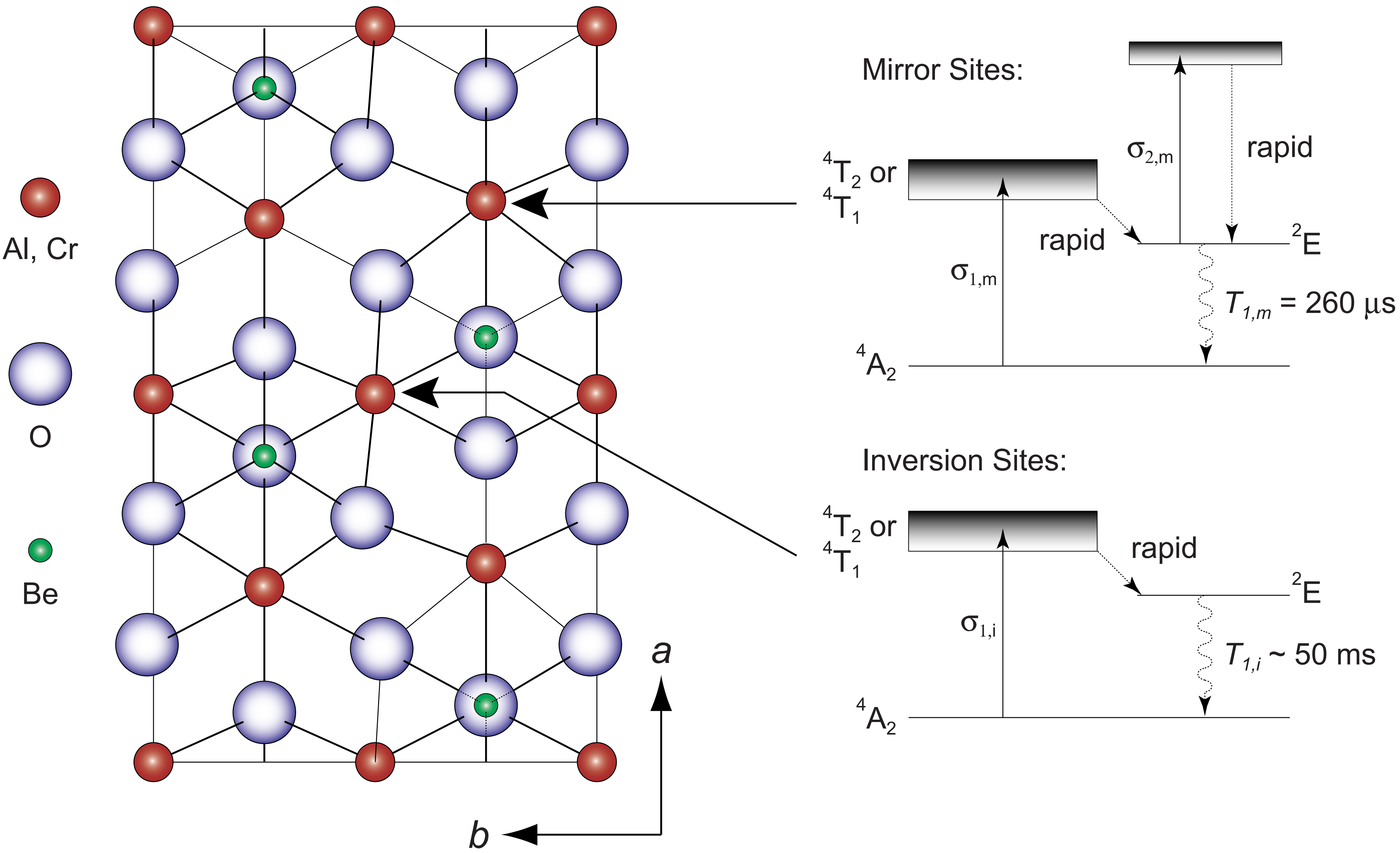
# Comparison of University of Rochester and University of Arizona



Bob and Ruby

Hyatt and Galina

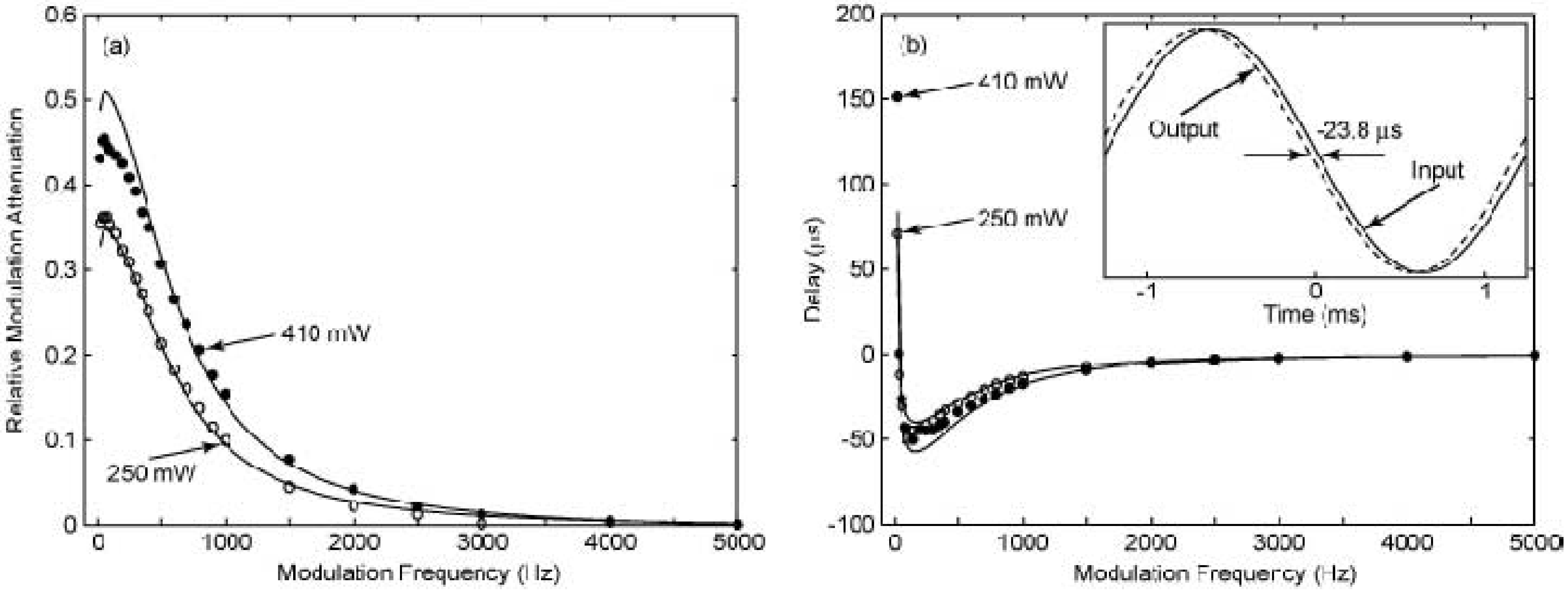
# Alexandrite Displays both Saturable and Inverse-Saturable Absorption



# 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 veleocity of -800 m/s



M. Bigelow, N. Lepeshkin, and RWB, Science, 2003

# Slow and Fast Light --What Next?

Longer fractional delay
(saturate deeper; propagate farther)

Find material with faster response
(technique works with shorter pulses)

# Research in Quantum Imaging

Can the 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.

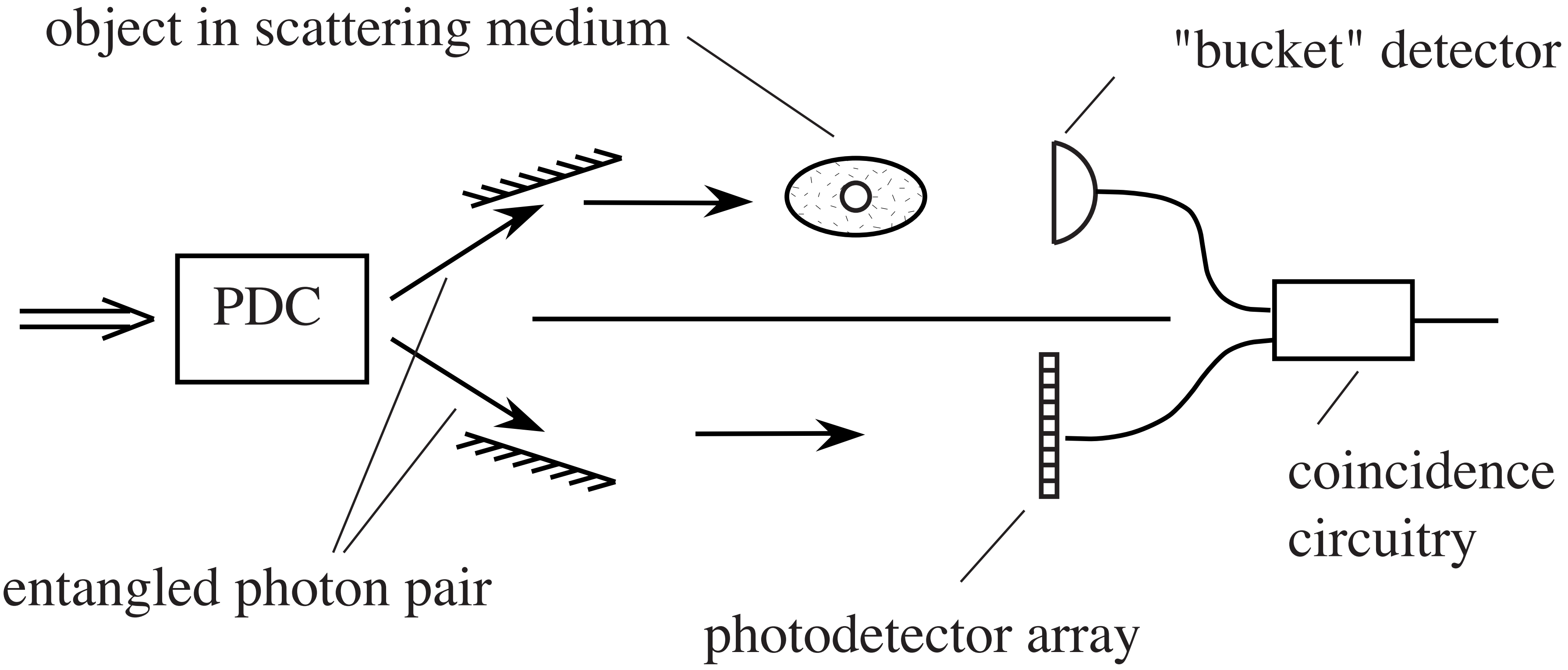
Founders:  Fabre, Klyshko, Kolobov, Kumar, Lugiato, Saleh, Sergienko, Shih, Teich.

# Research in Quantum Imaging

## Quantum Imaging or Quantum Imogene?

**Sid Caesar and
Imogene Coca in 1953**

# Quantum (?) Coincidence Imaging

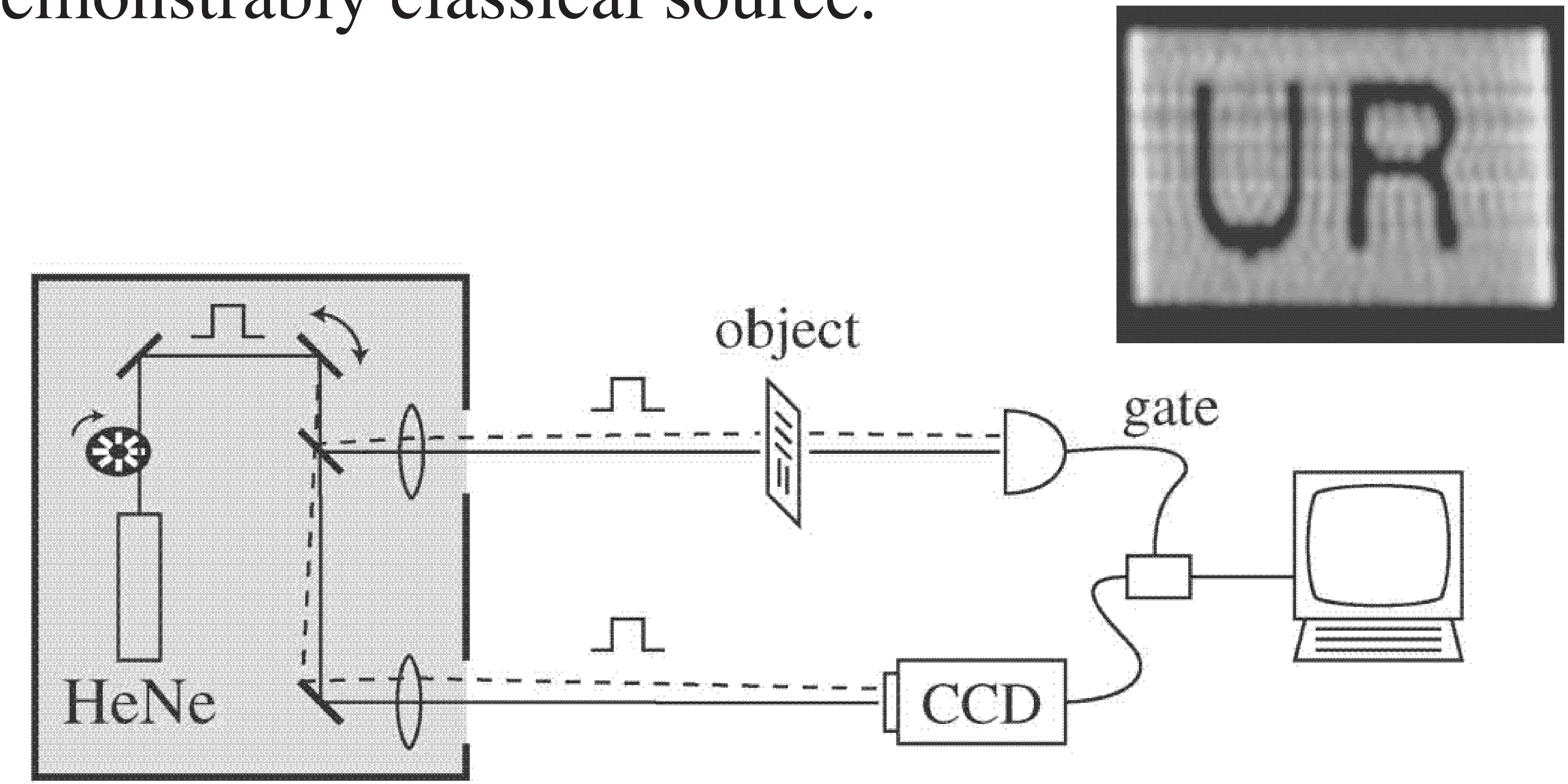


Obvious applicability to remote sensing!

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).

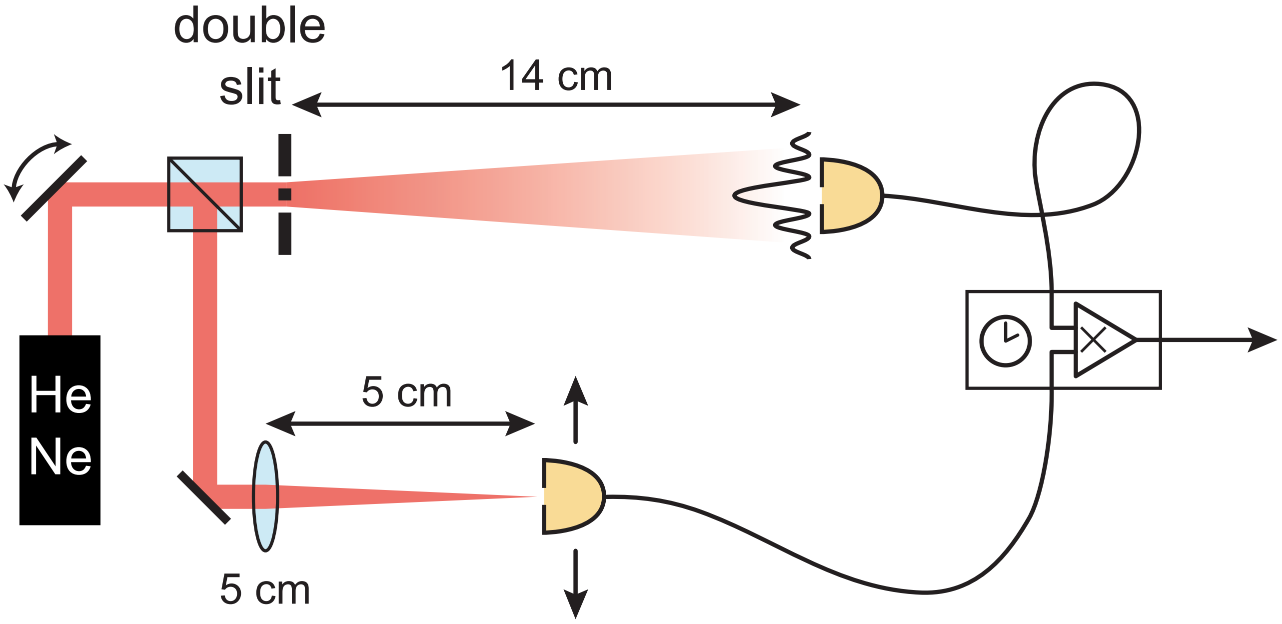
# Classical Coincidence Imaging

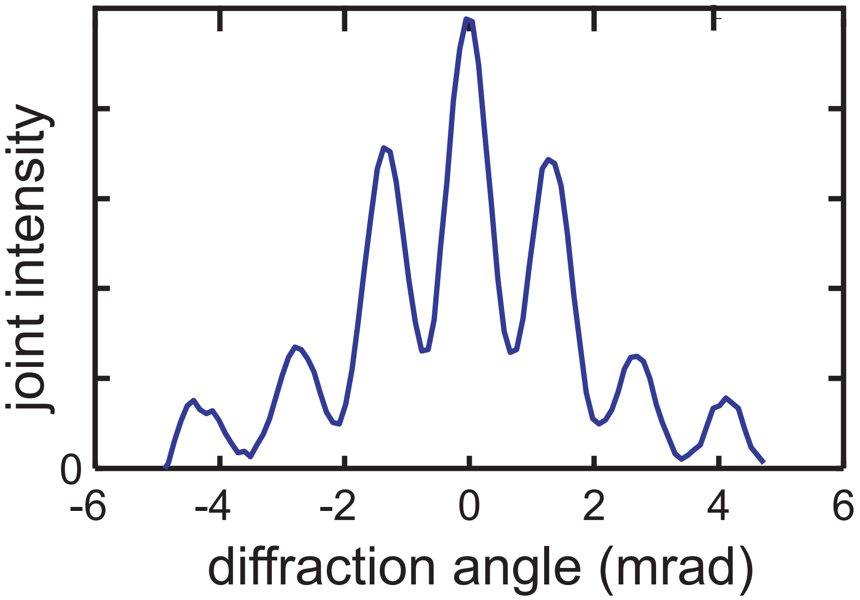
We have performed coincidence imaging with a demonstrably classical source.



Bennink, Bentley, and Boyd, Phys. Rev. Lett. **89** 113601(2002).

# Ghost Diffraction with a Classically Correlated Source





Even diffraction effects are observable with classical coincidence imaging.

# Recent Development

VOLUME 90, NUMBER 13 PHYSICAL REVIEW LETTERS week ending
4 APRIL 2003

## Entangled Imaging and Wave-Particle Duality: From the Microscopic to the Macroscopic Realm

A. Gatti, E. Brambilla, and L. A. Lugiato

*INFM, Dipartimento di Scienze CC.FF.MM., Università dellíInsubria, Via Valleggio 11, 22100 Como, Italy*

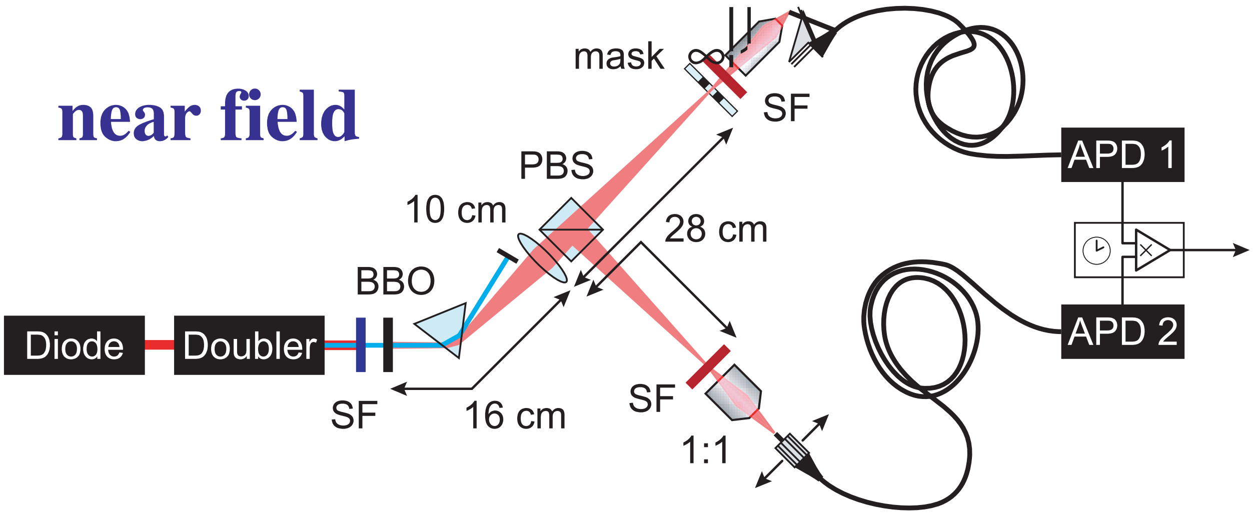
(Received 11 October 2002; published 3 April 2003)

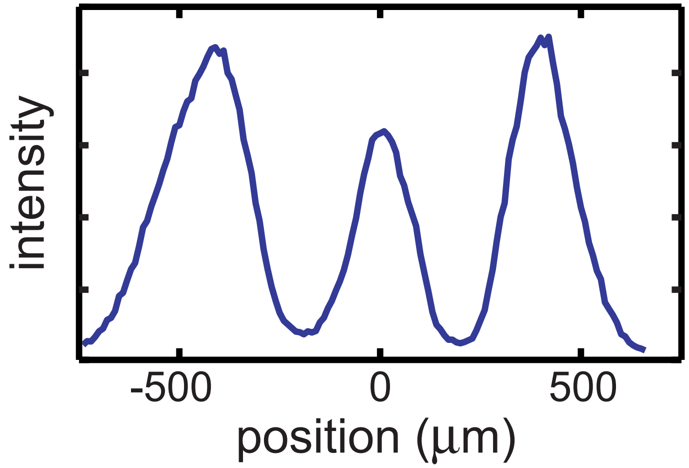
We formulate a theory fo~~r entan~~gled imaging, which includes also the case of a large number of photons in the two entangled beams. We show that the results for imaging and for the wave-particle duality features, which have been demonstrated in the microscopic case, persist in the macroscopic domain. We show that the quantum character of the imaging phenomena is guaranteed by the simultaneous spatial entanglement in the near and in the far field.

DOI: 10.1103/PhysRevLett.90.133603 PACS numbers: 42.50.Dv, 03.65.Ud

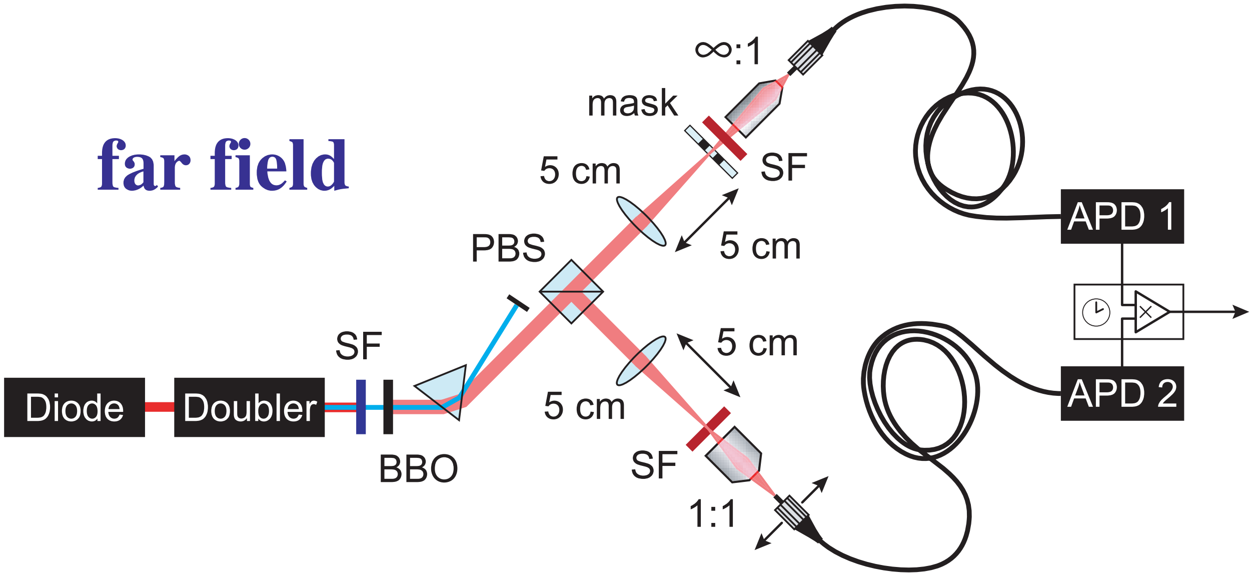
# Near- and Far-Field Imaging Using Quantum Entanglement

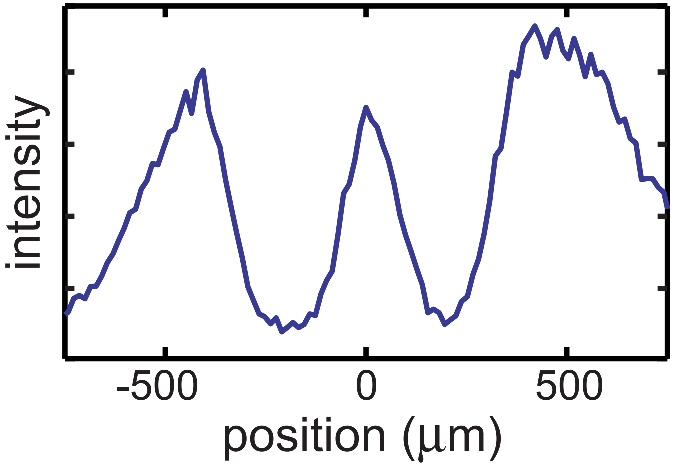
## near field





## far field



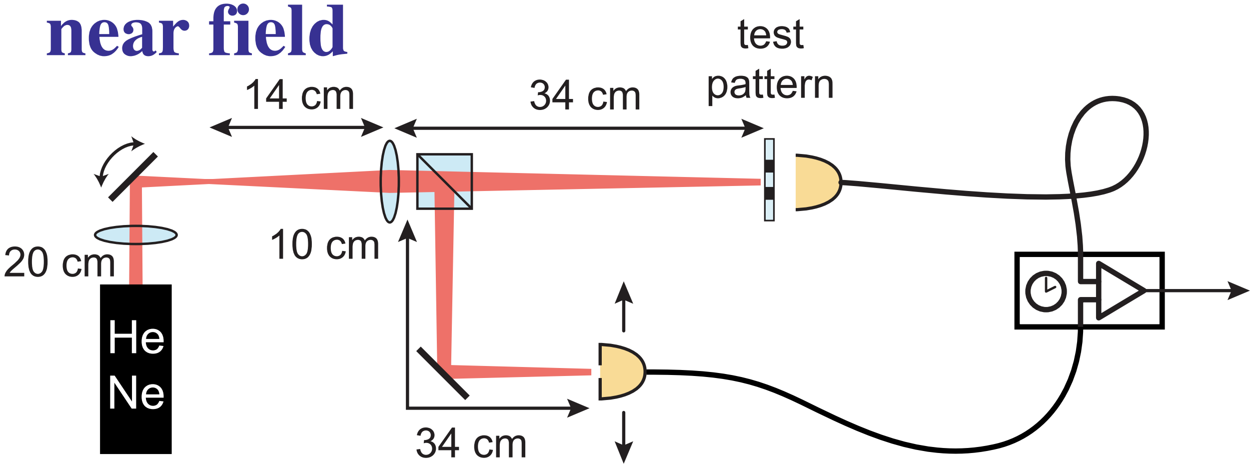


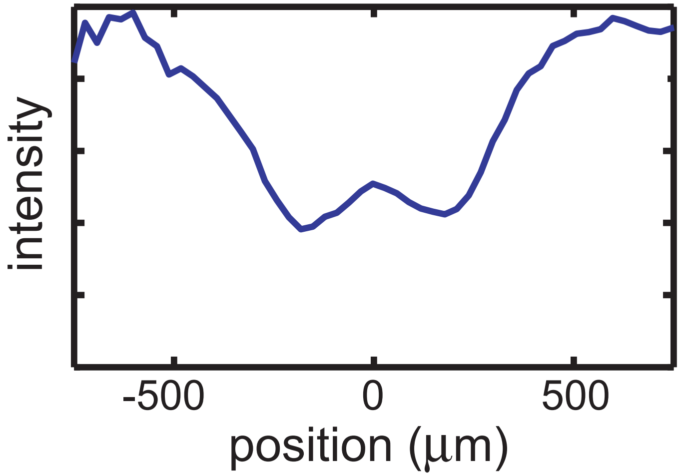
Good imaging observed in both the near and far fields.

R. Bennink, S. Bentley, R. Boyd, and J. Howell

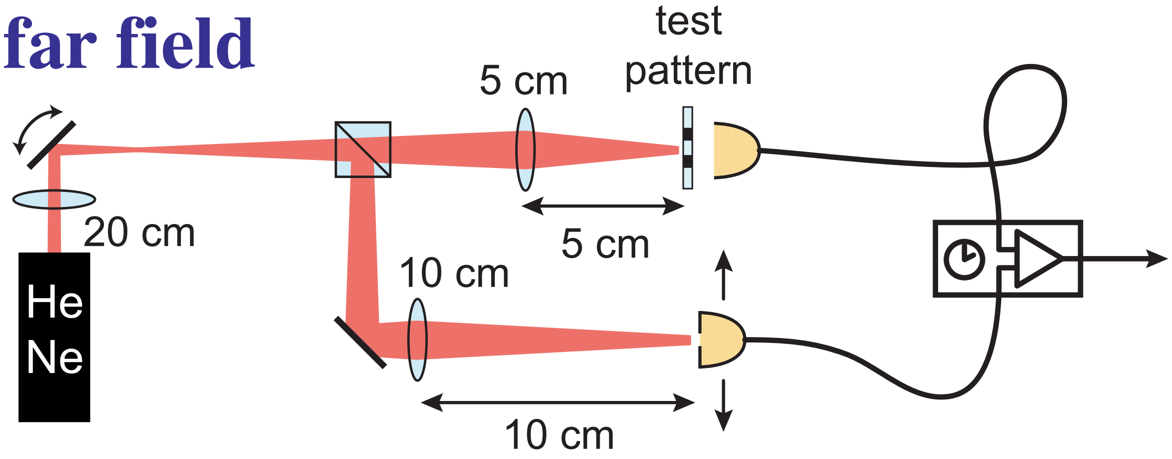
# Near- and Far-Field Imaging With a Classical Source

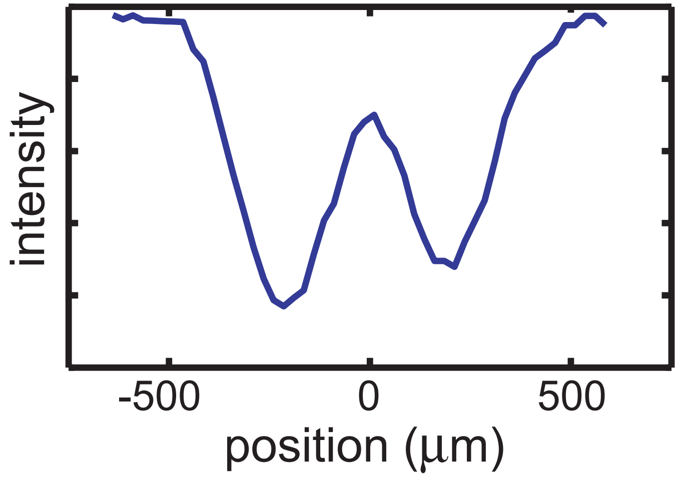
## near field





## far field

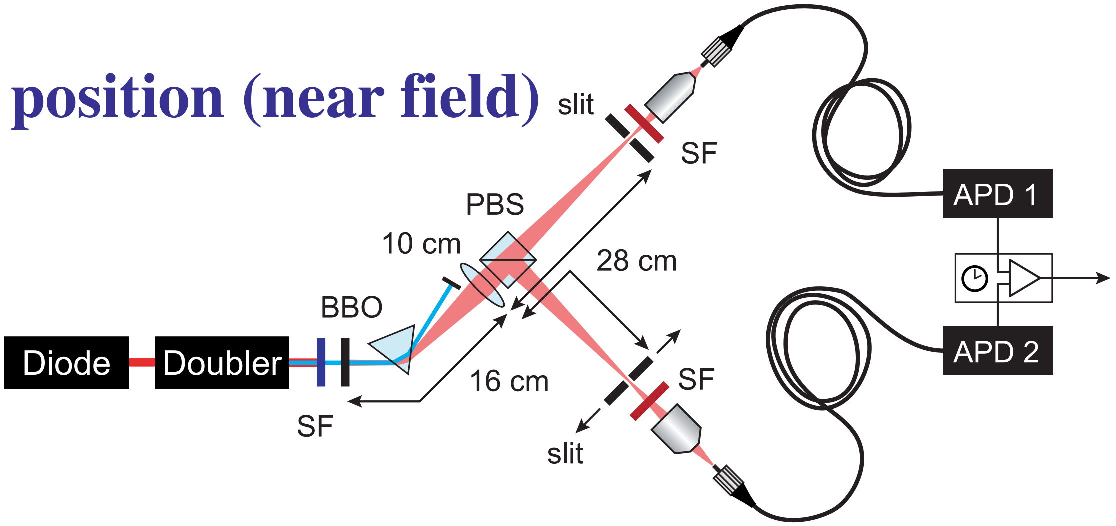


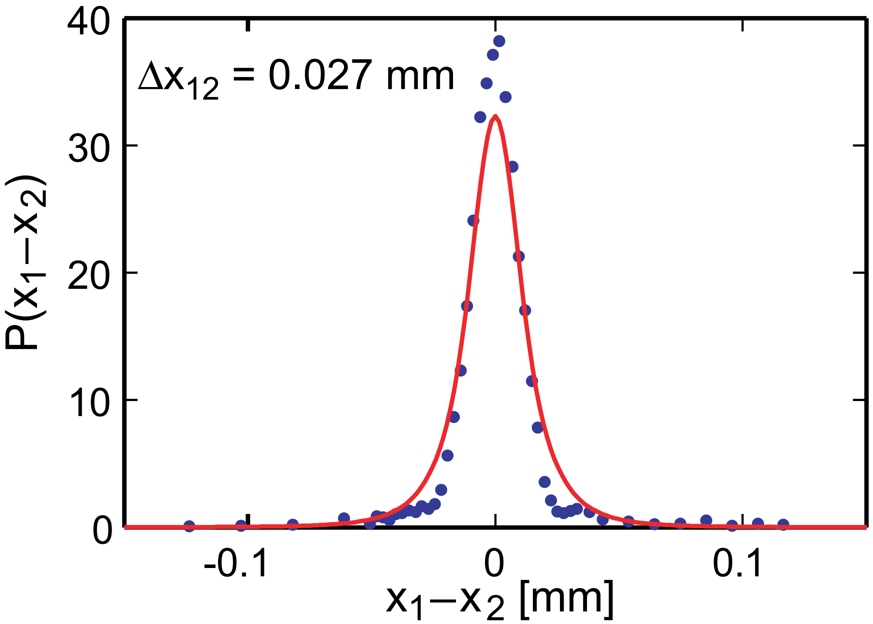


- Good imaging can be obtained only in near field **or** far field.
- Detailed analysis shows that in the quantum case the space-bandwidth exceeded the classical limit by a factor of three.

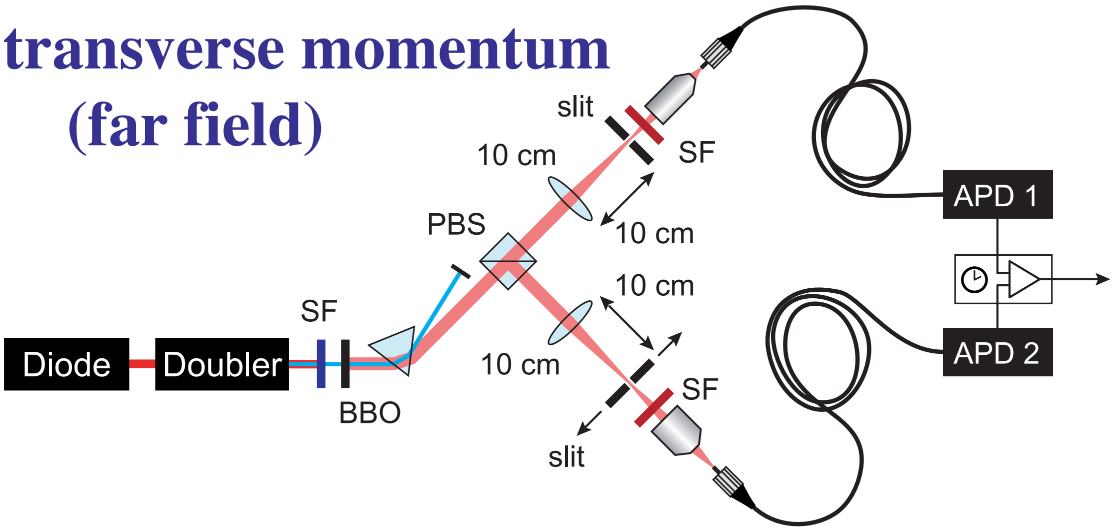
# Position-Momentum Realization of the EPR Paradox

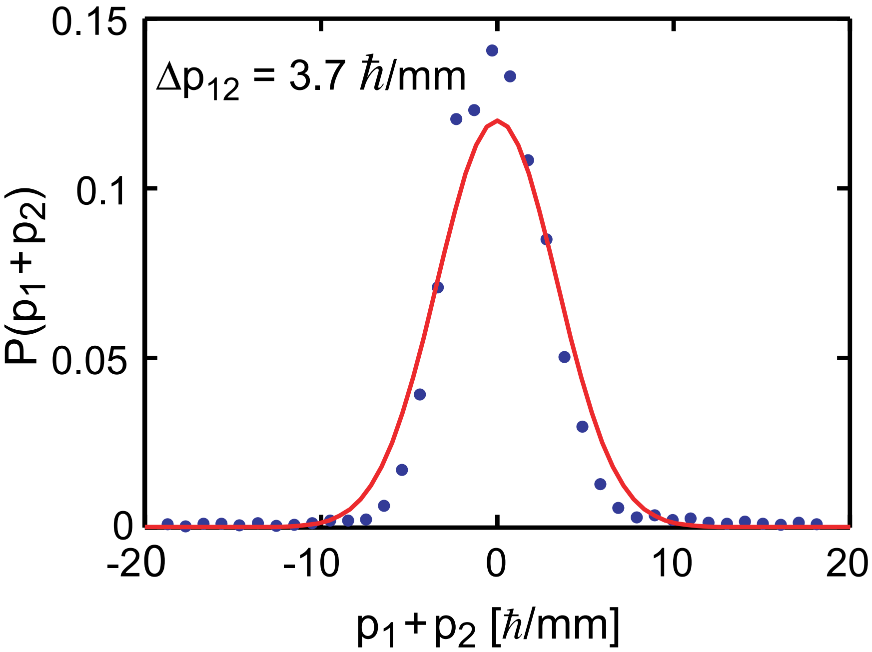
**position (near field)**





**transverse momentum (far field)**





- We find that $\Delta x_{12}\, \Delta p_{12} = 0.1\ (h/2\pi)$

# The Promise of Nonlinear Optics

Nonlinear optical techniques hold great promise for applications including:

- Photonic Devices
- Quantum Imaging
- Quantum Computing/Communications
- Optical Switching
- Optical Power Limiters
- All-Optical Image Processing

But the lack of high-quality photonic materials is often the chief limitation in implementing these ideas.

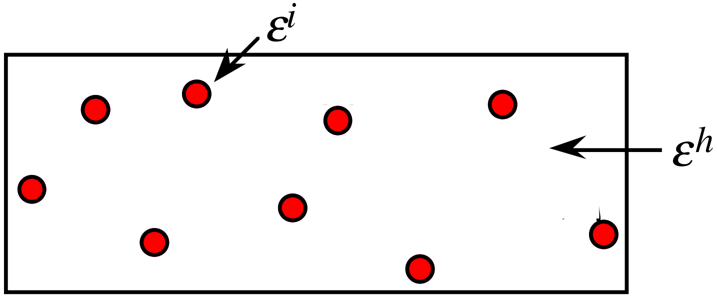
# Approaches to the Development of Improved NLO Materials

- New chemical compounds
- Quantum coherence (EIT, etc.)
- Composite Materials:
  - (a) Microstructured Materials, e.g.
    Photonic Bandgap Materials,
    Quasi-Phasematched Materials, etc
  - (b) Nanocomposite Materials

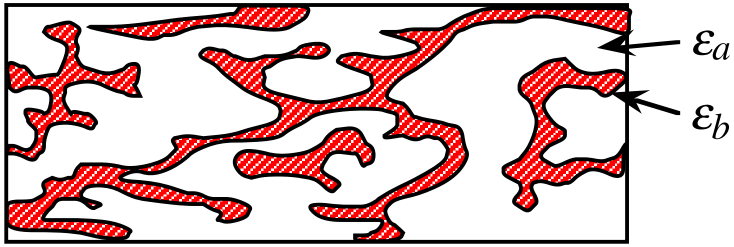
These approaches are not incompatible and in fact can be exploited synergistically!

# Nanocomposite Materials for Nonlinear Optics

- Maxwell Garnett

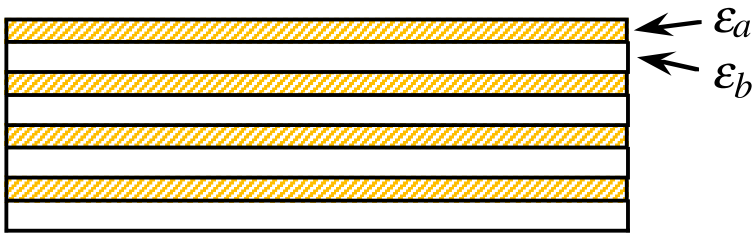


- Bruggeman (interdispersed)



- Fractal Structure

- Layered



scale size of inhomogeneity << optical wavelength

# Gold-Doped Glass: A Maxwell-Garnett Composite

**Developmental Glass, Corning, Inc.**

gold volume fraction approximately $10^{-6}$

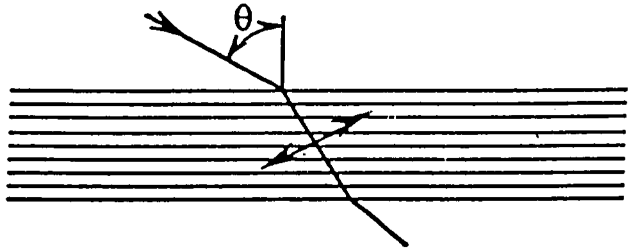
gold particles approximately 10 nm diameter

**Red Glass Caraffe,**
Nurenberg, ca. 1700
Huelsmann Museum, Bielefeld

- Composite materials can possess properties very different from those of their constituents
- Red color is because the material absorbs very strongly at the surface plasmon frequency, which is in the blue.

# Demonstration of Enhanced NLO Response

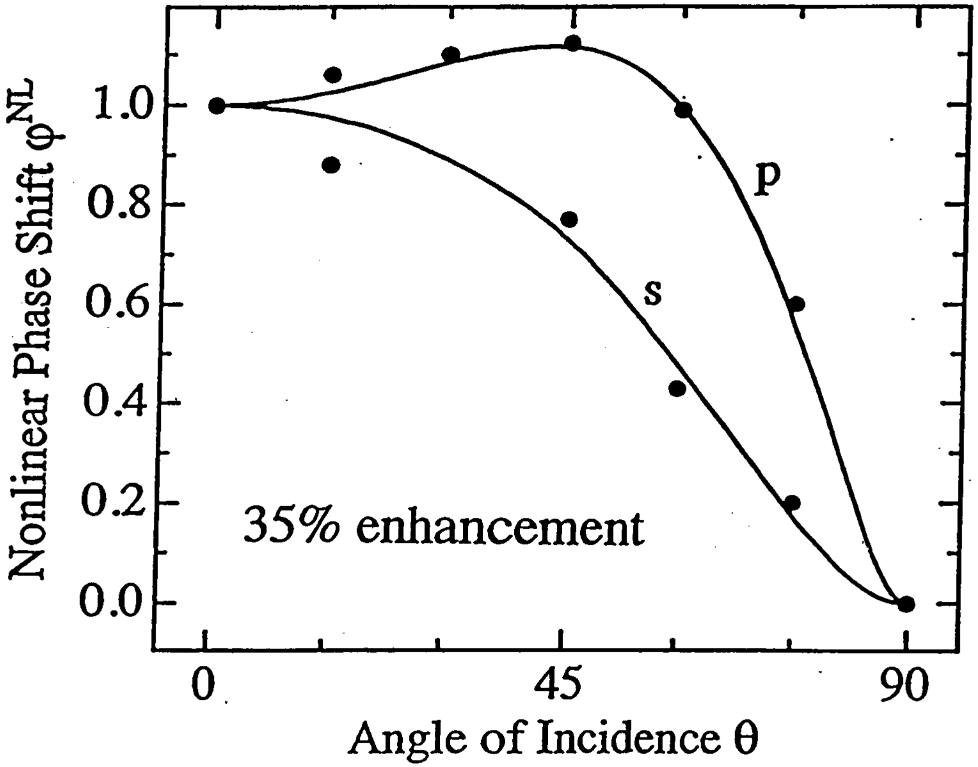
- Alternating layers of $TiO_2$ and the conjugated polymer PBZT.



$\nabla \cdot \mathbf{D} = 0$ implies that $(\varepsilon \mathbf{E})_\perp$ is continuous.

Thus field is concentrated in *lower* index material.

- Measure NL phase shift as a function of angle of incidence

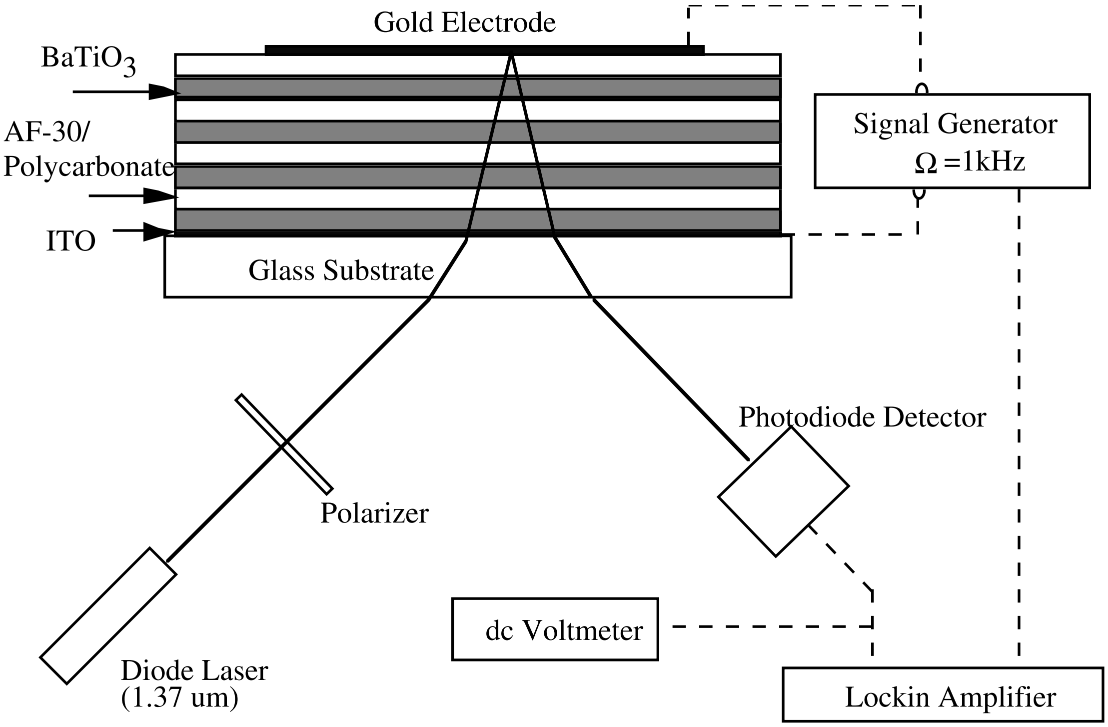


35% enhancement

Fischer, Boyd, Gehr, Jenekhe, Osaheni, Sipe, and Weller-Brophy, Phys. Rev. Lett. 74, 1871, 1995.

Gehr, Fischer, Boyd, and Sipe, Phys. Rev. A 53, 2792 1996.

# Enhanced EO Response of Layered Composite Materials



$$\chi^{(eff)}_{ijkl}(\omega';\omega,\Omega_1,\Omega_2) = f_a\left[\frac{\varepsilon_{eff}(\omega')}{\varepsilon_a(\omega')}\right]\left[\frac{\varepsilon_{eff}(\omega)}{\varepsilon_a(\omega)}\right]\left[\frac{\varepsilon_{eff}(\Omega_1)}{\varepsilon_a(\Omega_1)}\right]\left[\frac{\varepsilon_{eff}(\Omega_2)}{\varepsilon_a(\Omega_2)}\right]\chi^{(a)}_{ijkl}(\omega';\omega,\Omega_1,\Omega_2)$$

- AF-30 (10%) in polycarbonate (spin coated)
  n=1.58 ε(dc) = 2.9
- barium titante (rf sputtered)
  n=1.98 ε(dc) = 15

$$\chi^{(3)}_{zzzz} = (3.2 + 0.2i)\times 10^{-21}\ (m/V)^2 \pm 25\%$$

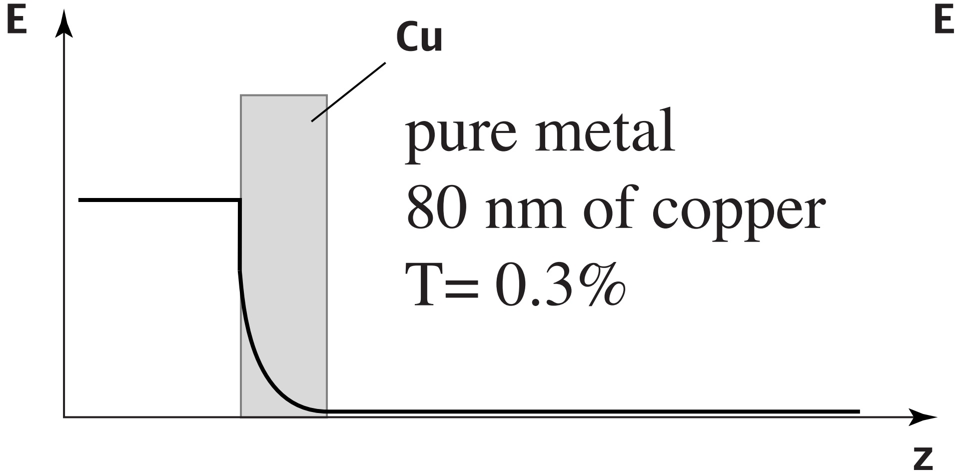
$$\approx 3.2\ \chi^{(3)}_{zzzz}(\text{AF-30 / polycarbonate})$$

3.2 times enhancement in agreement with theory

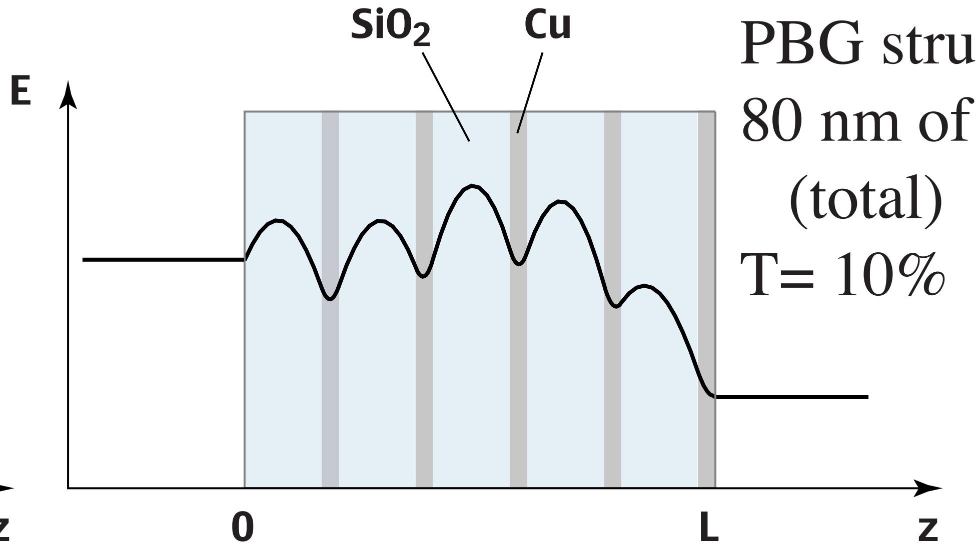
R. L. Nelson, R. W. Boyd, Appl. Phys. Lett. 74, 2417, 1999.

# Accessing the Optical Nonlinearity of Metals with Metal-Dielectric PBG Structures

- Metals have very large optical nonlinearities but low transmission.
- Low transmission is because metals are highly reflecting (not because they are absorbing!).
- Solution: construct metal-dielectric PBG structure.
  (linear properties studied earlier by Bloemer and Scalora)



pure metal
80 nm of copper
T= 0.3%



PBG structure
80 nm of Cu
(total)
T= 10%

40 times enhancment of NLO response is predicted!

R.S. Bennink, Y.K. Yoon, R.W. Boyd, and J. E. Sipe Opt. Lett. 24, 1416, 1999.

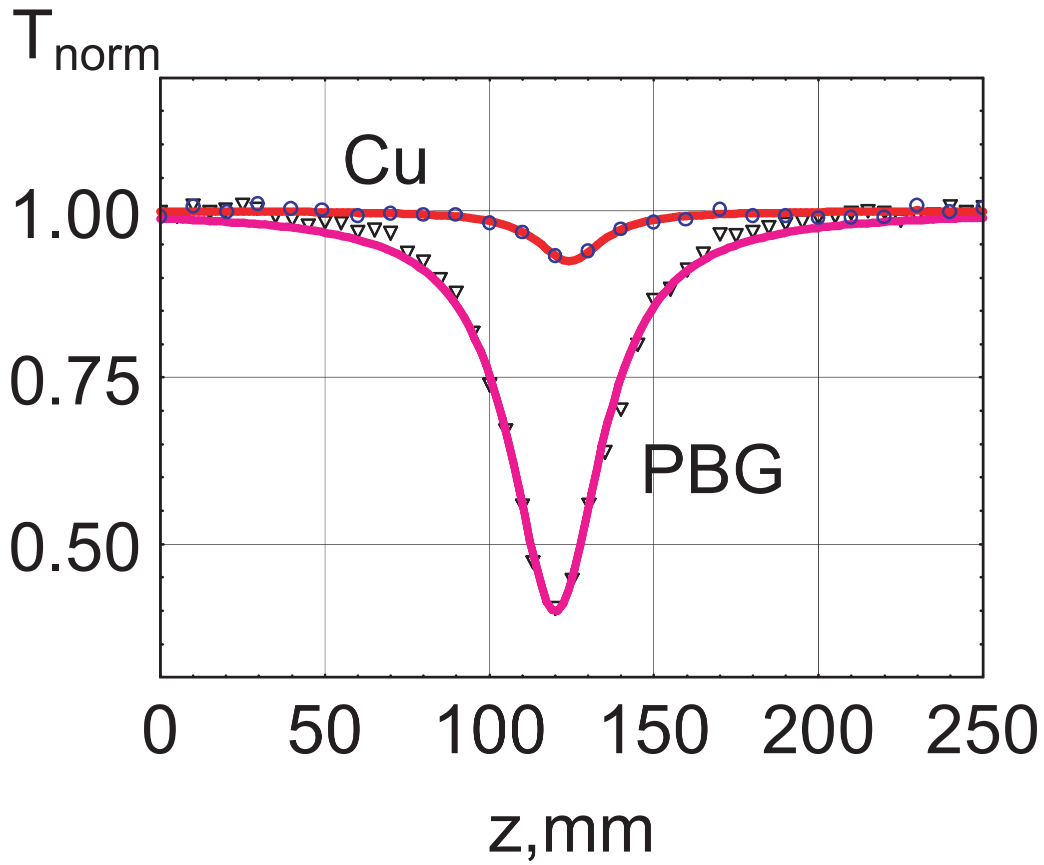
# Z-Scan Comparison of M/D PBG and Bulk Sample

Open-aperture Z-scan

(measures Im $\chi^{(3)}$)

$I = 500\ \mathrm{MW/cm}^2$

$\lambda = 640\ \mathrm{nm}$

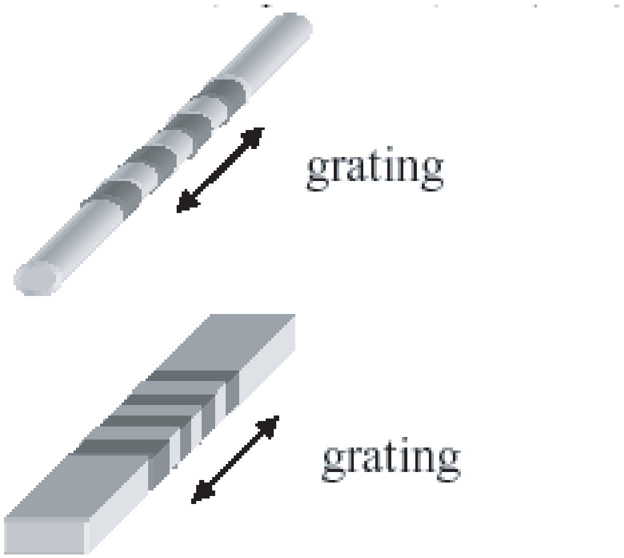


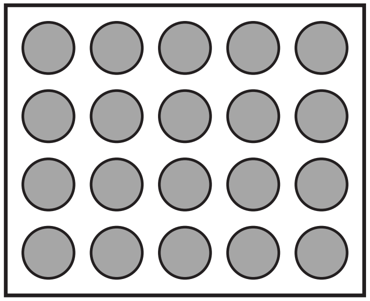
$$\frac{\delta\phi''_{\mathbf{PBG}}}{\delta\phi''_{\mathbf{Cu}}} \cong 35$$

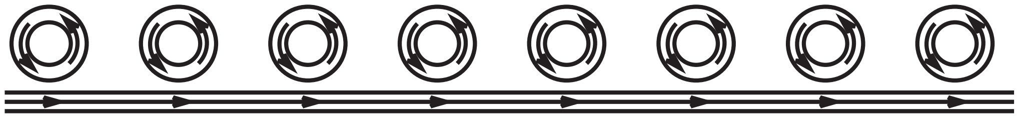
# Artificial Materials for Nonlinear Optics

Artifical materials can produce
- Large nonlinear optical response
- Large dispersive effects

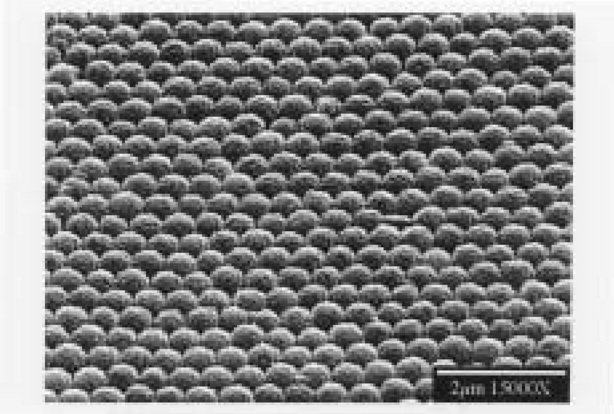
Examples
- Fiber/waveguide Bragg gratings
- PBG materials
- CROW devices (Yariv et al.)
- SCISSOR devices





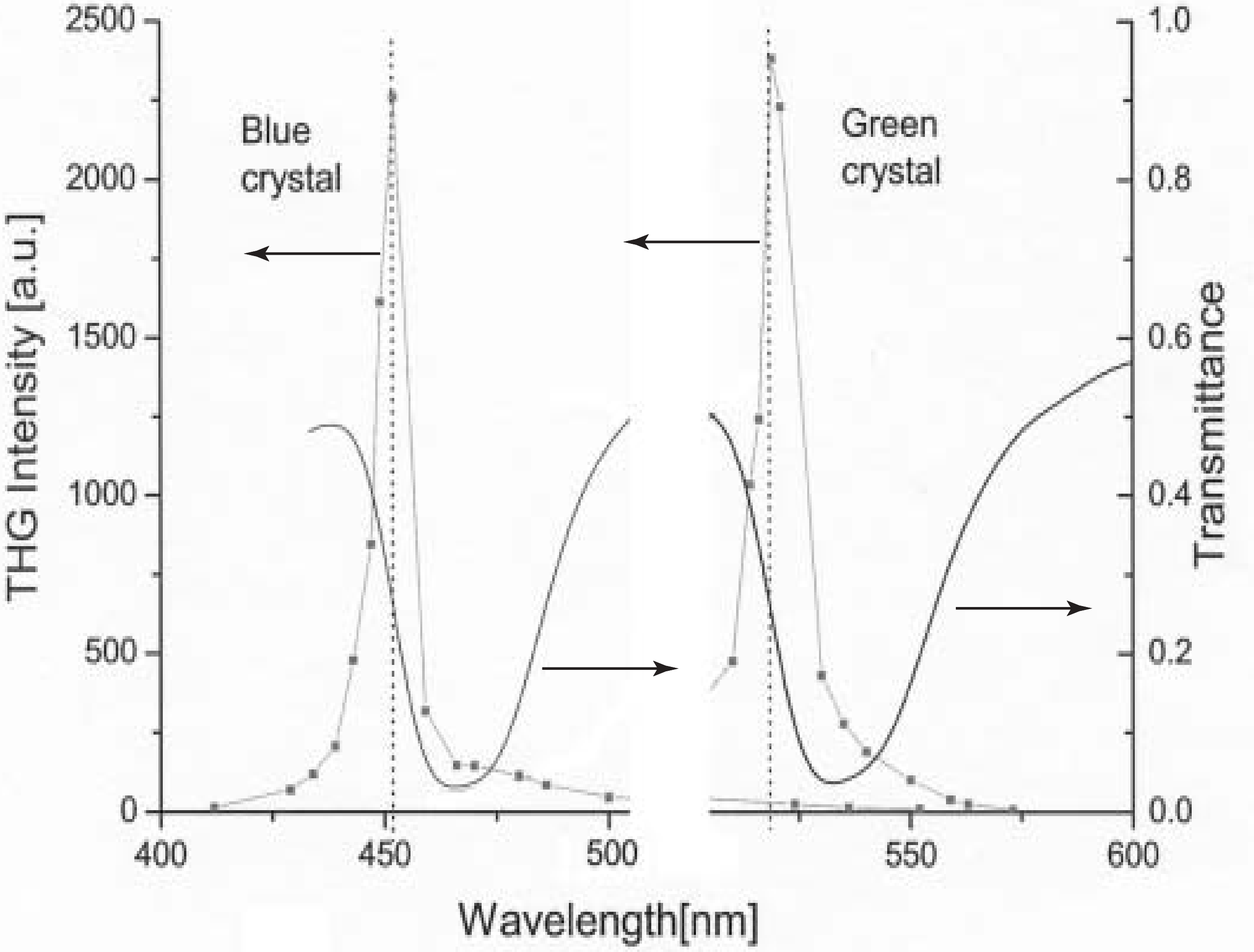


# Third Harmonic Generation in a 3-D Photonic Crystal



polystyrene photonic crystal

Direct THG visible by eye!

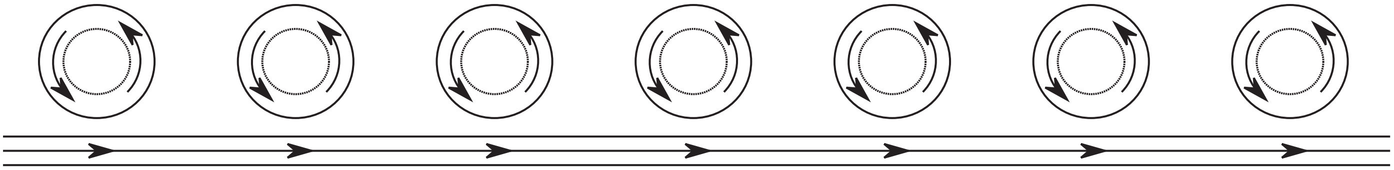


Phase matching provided by PBG structure.

Joint with P.N. Prasad et al., SUNY Buffalo

# NLO of SCISSOR Devices

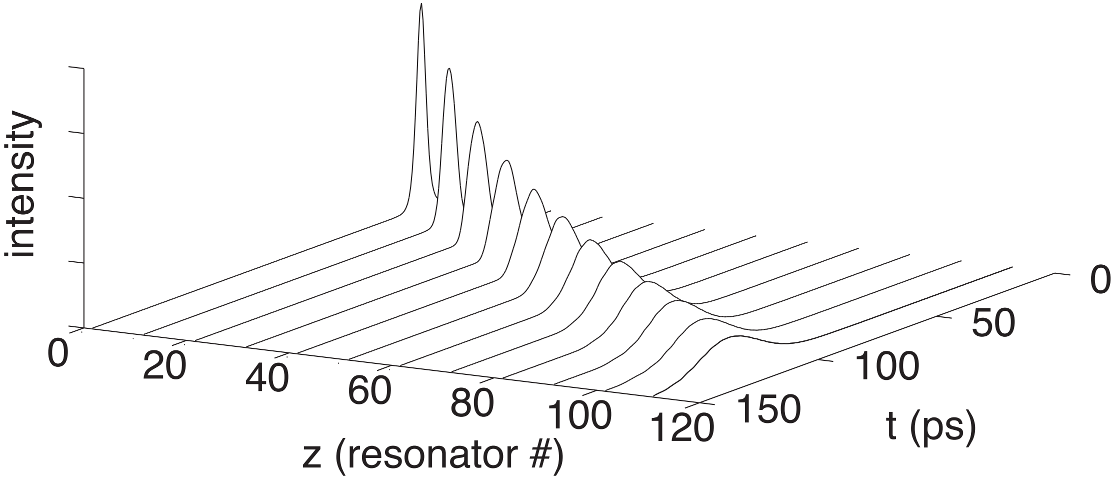
(Side-Coupled Integrated Spaced Sequence of Resonators)



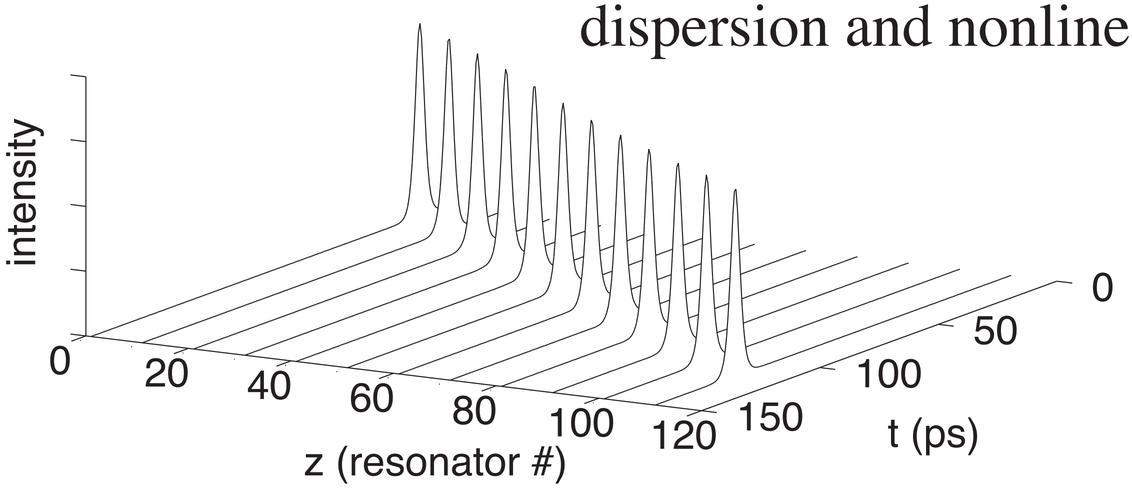
Shows slow-light, tailored dispersion, and enhanced nonlinearity

Optical solitons described by nonlinear Schrodinger equation

- Weak pulses spread because of dispersion

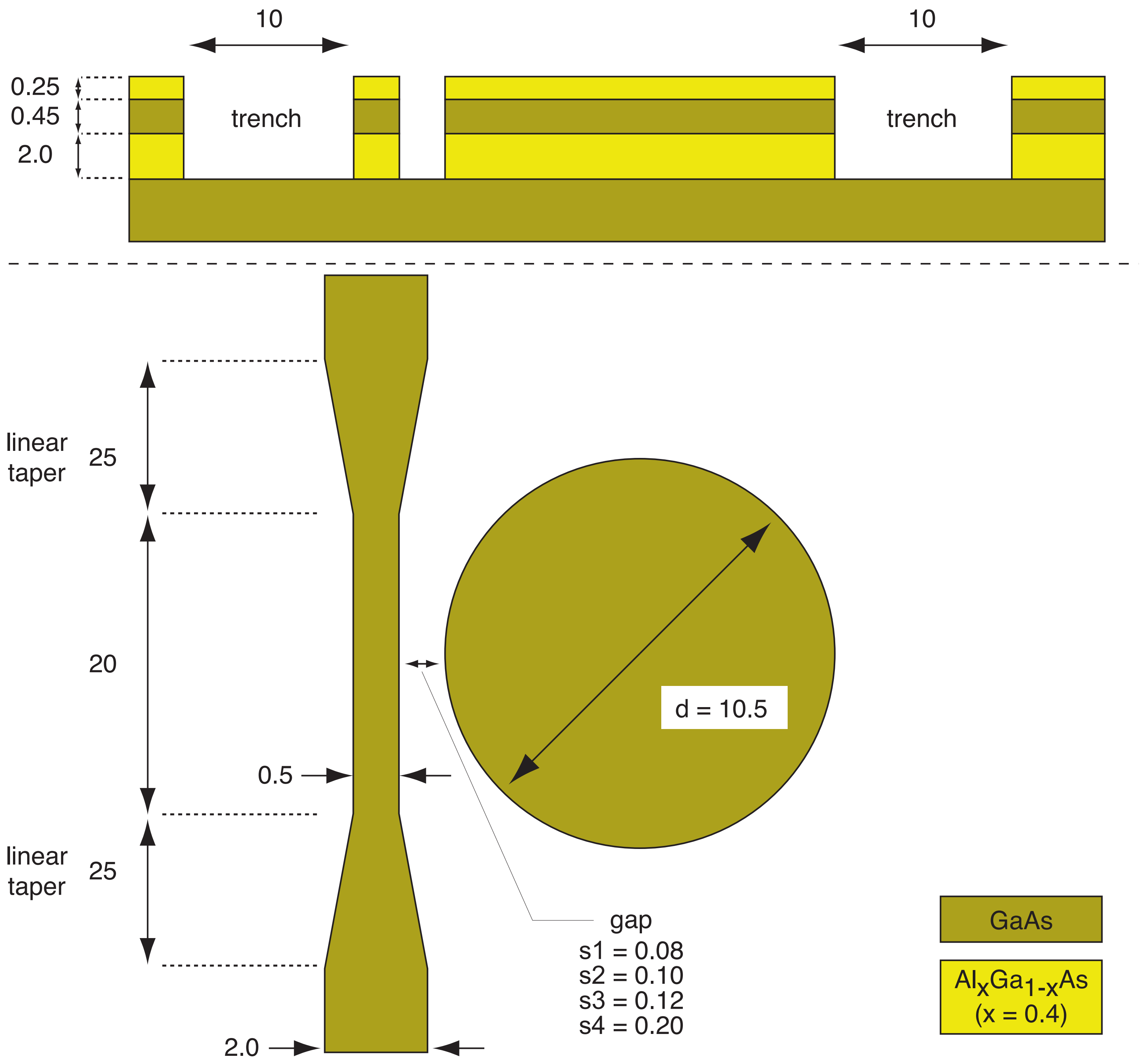


- But intense pulses form solitons through balance of dispersion and nonlinearity.



# Microdisk Resonator Design

All dimensions in microns



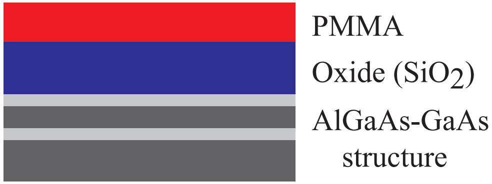
J. E. Heebner and R. W. Boyd

# Photonic Device Fabrication Procedure

### (1) MBE growth

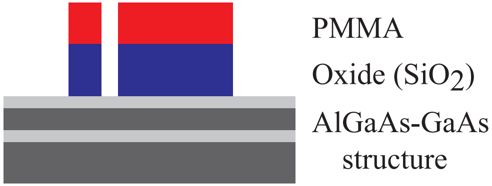
### (2) Deposit oxide

### (3) Spin-coat e-beam resist



### (4) Pattern inverse with e-beam & develop

### (5) RIE etch oxide

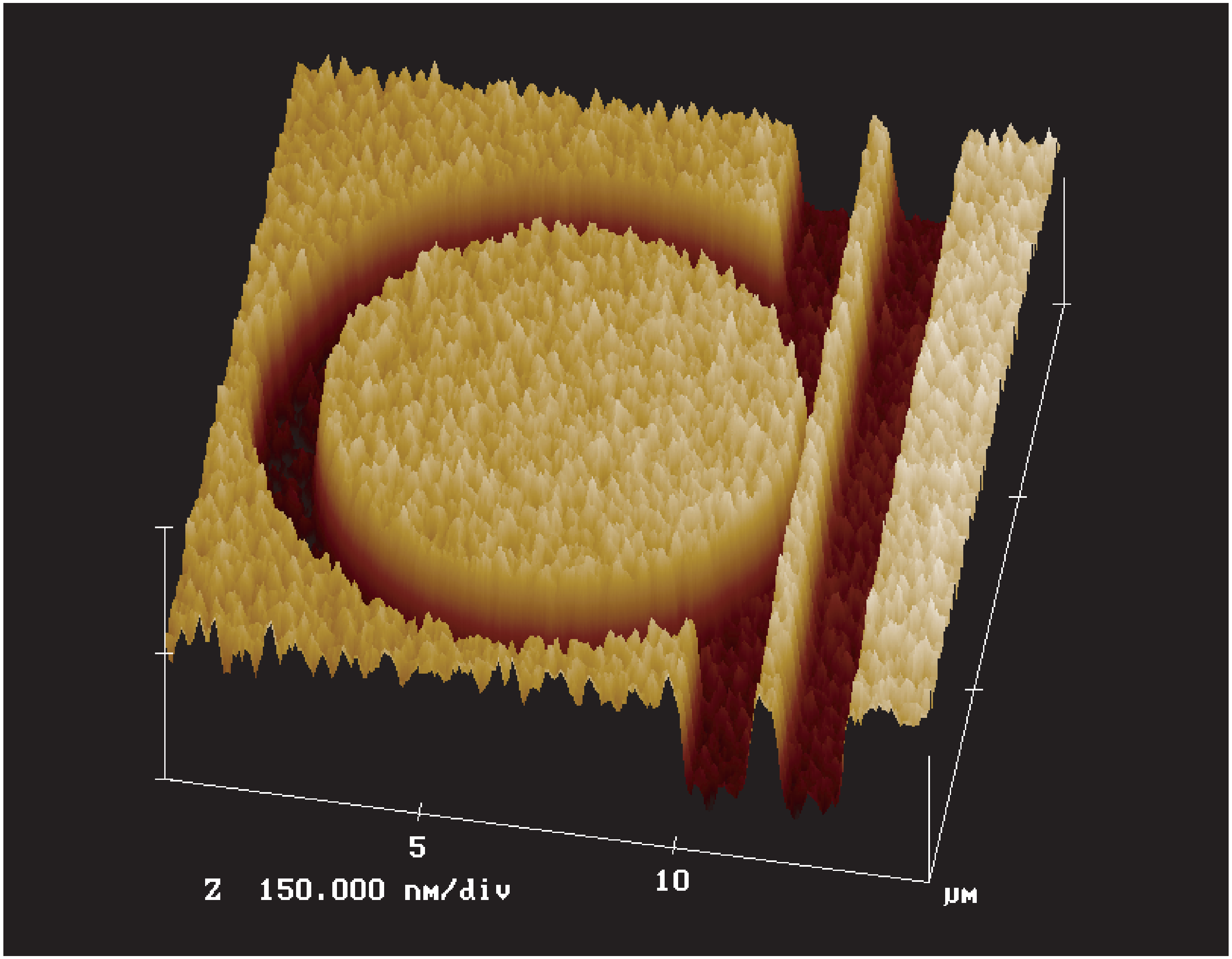


### (6) Remove PMMA

### (7) CAIBE etch AlGaAs-GaAs

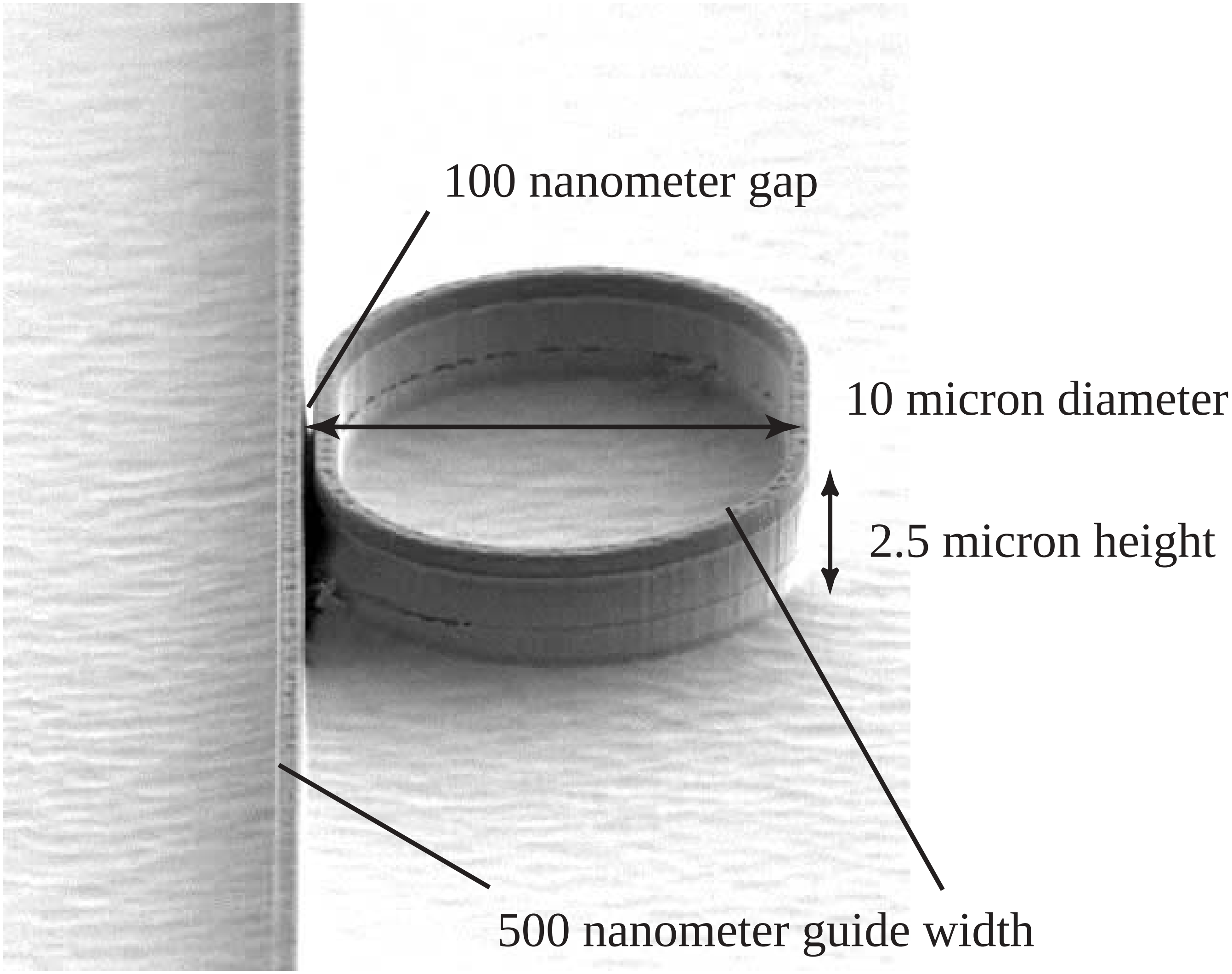
### (8) Strip oxide

# Disk Resonator and Optical Waveguide in PMMA Resist



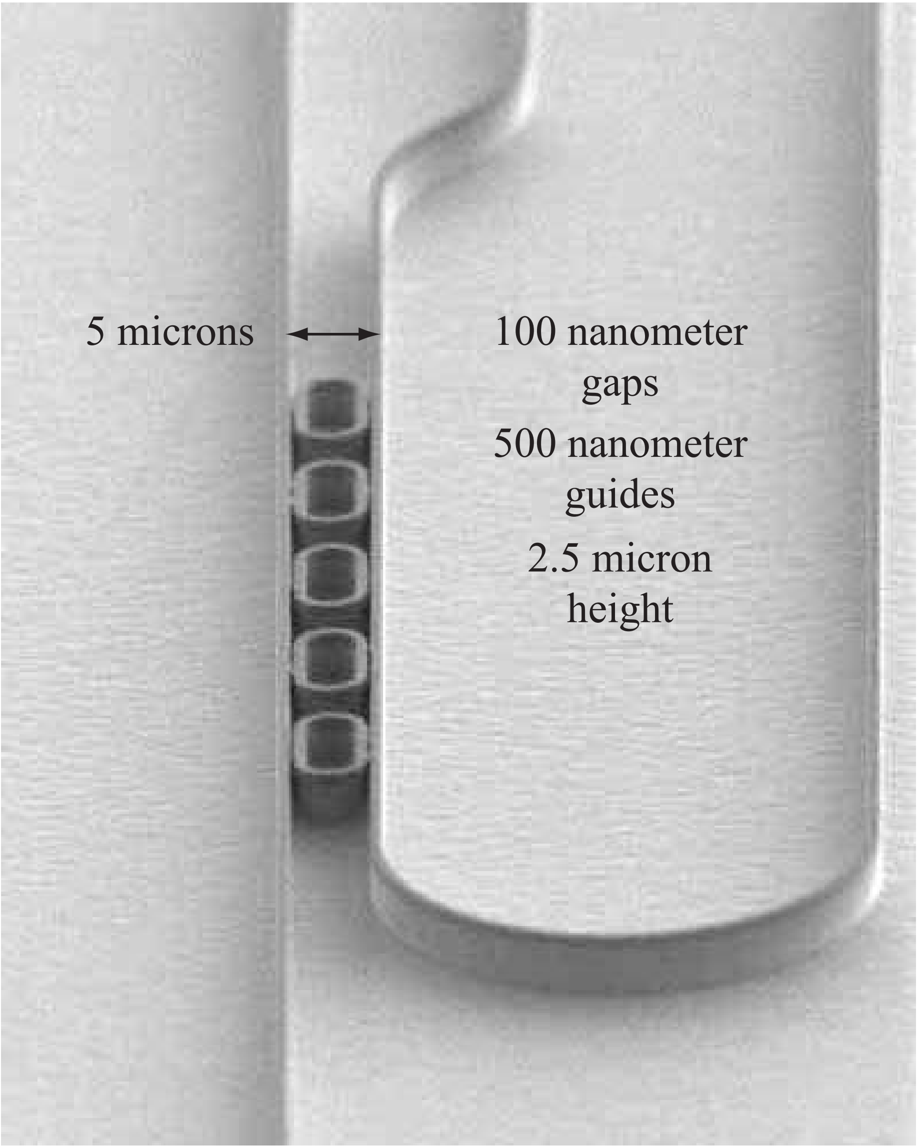
AFM

# All-Pass Racetrack Microresonator

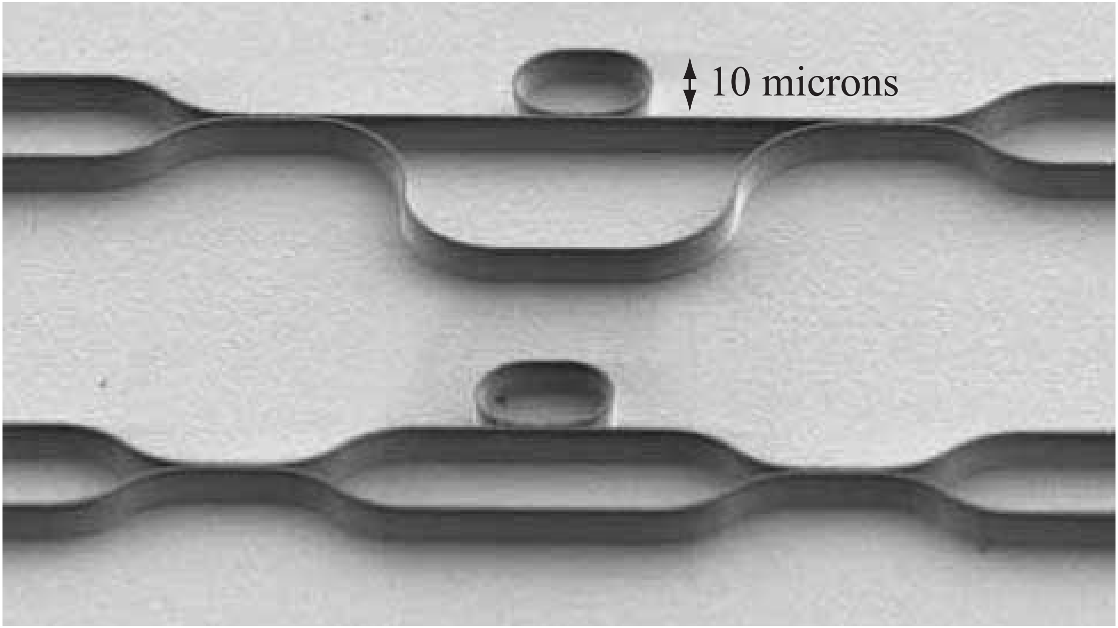


Thanks to P.T. Ho and R. Grover, U. Maryland, for help with final etch.

# Five-Cell SCISSOR with Tap Channel



# Resonator-Enhanced Mach-Zehnder Interferometers



~100 nanometer gaps

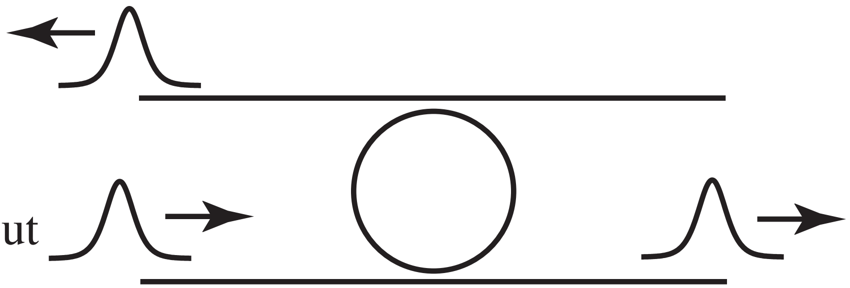
500 nanometer guides

2.5 micron height

# Laboratory Characterization of Photonic Structures

- Characterization of fiber ring-resonator devices (Proof of principle studies)
- Characterization of nanofabricated devices

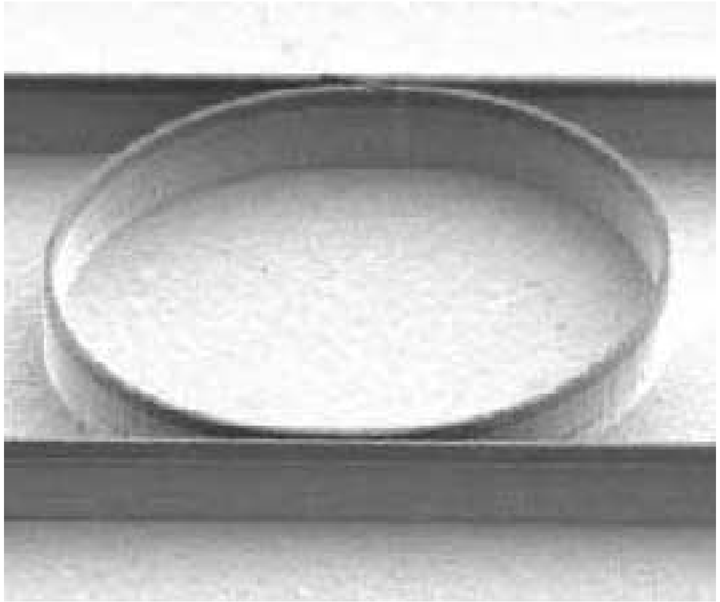
# Microresonator-Based Add-Drop Filter

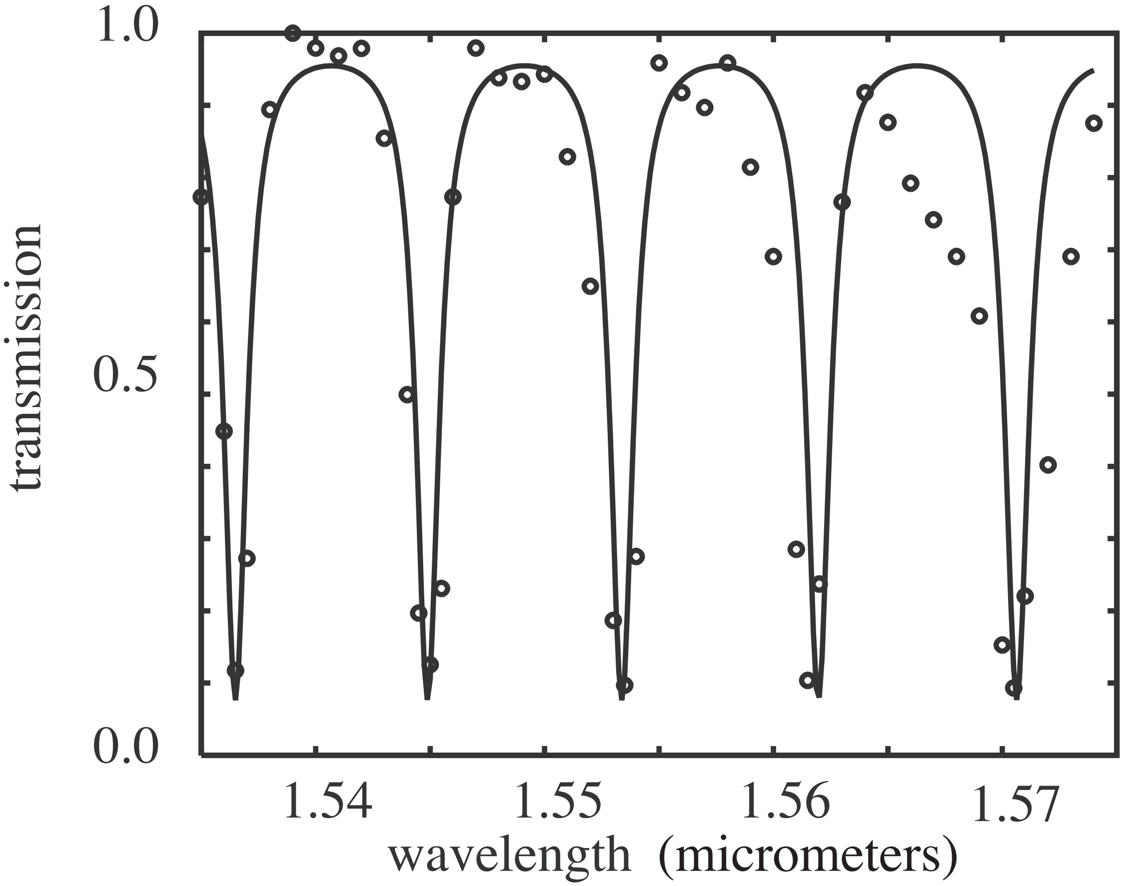


output for
on-resonance input

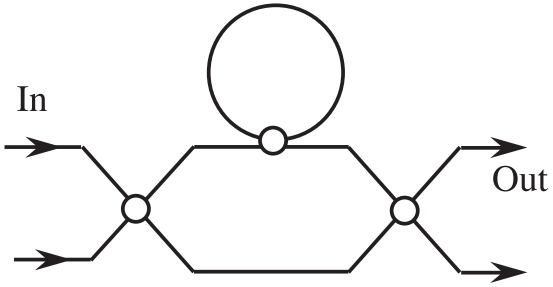
variable wavelength input

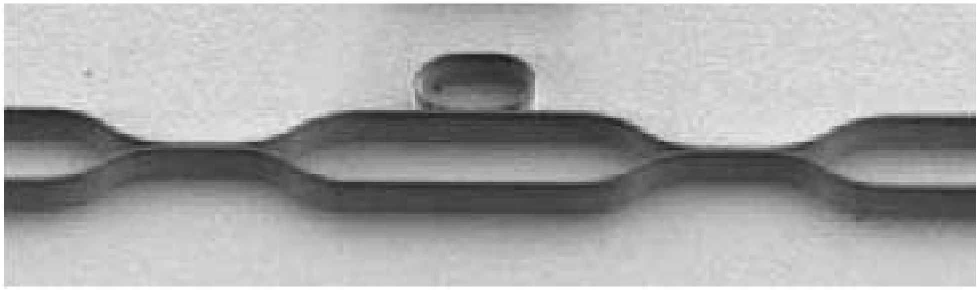
output for
off-resonance input



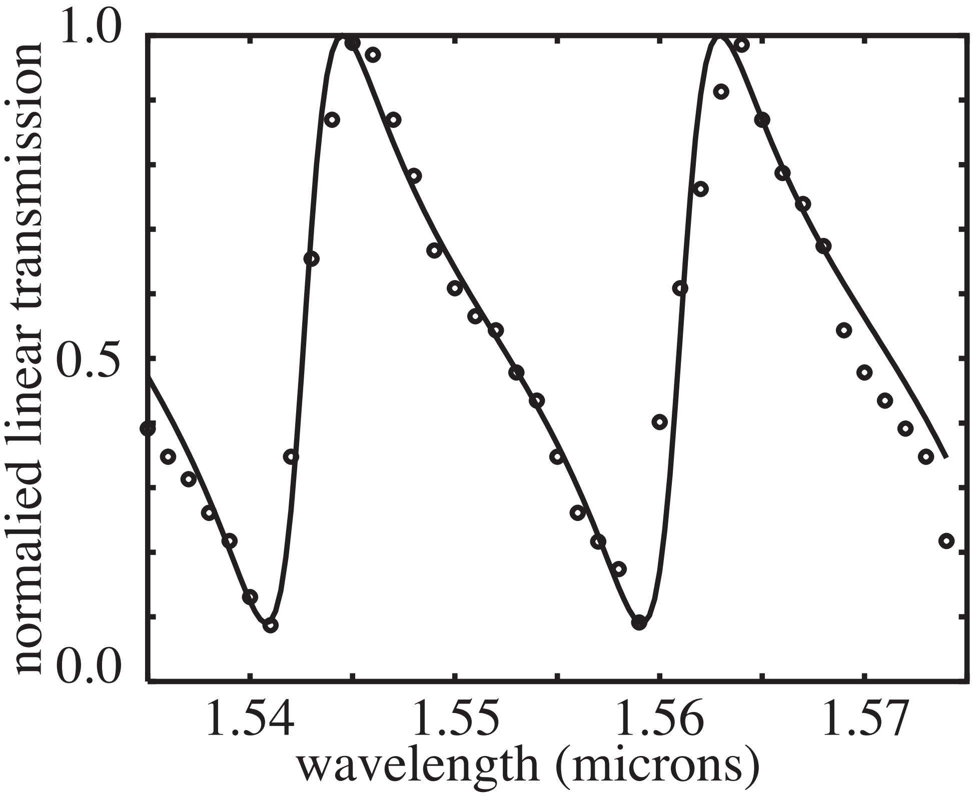


# Phase Characteristics of Micro-Ring Resonator

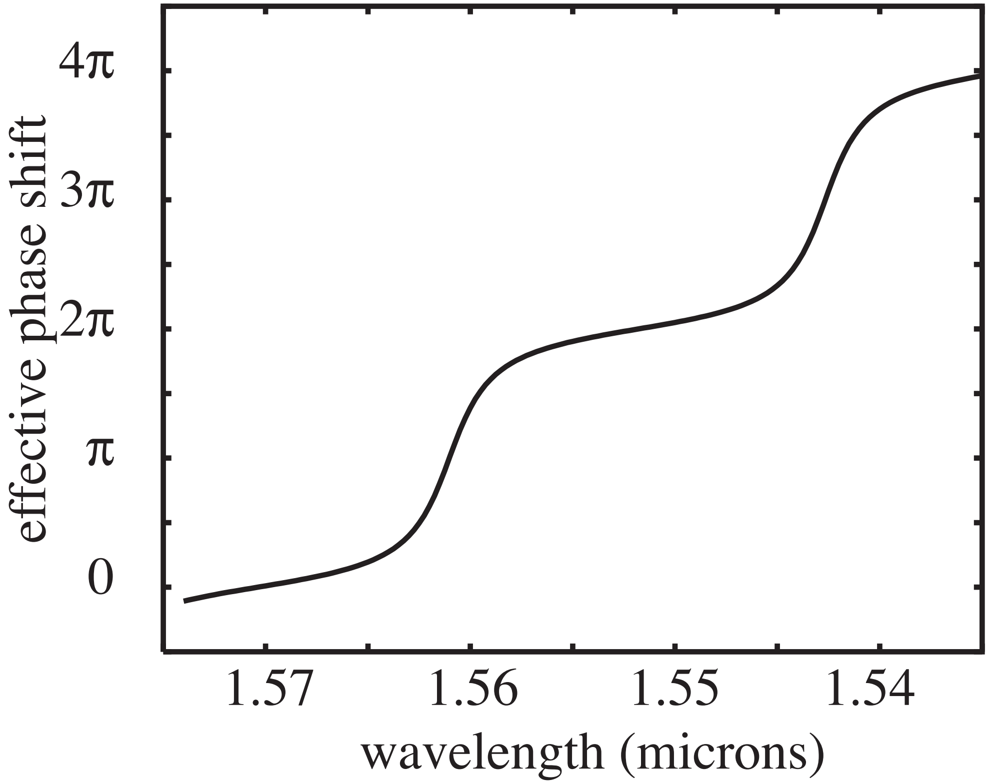




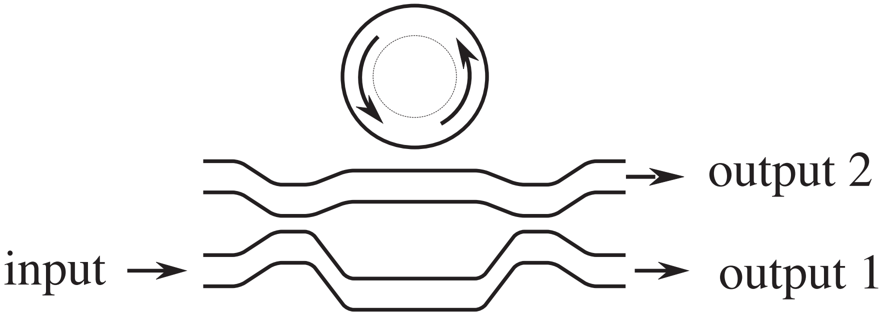
transmission

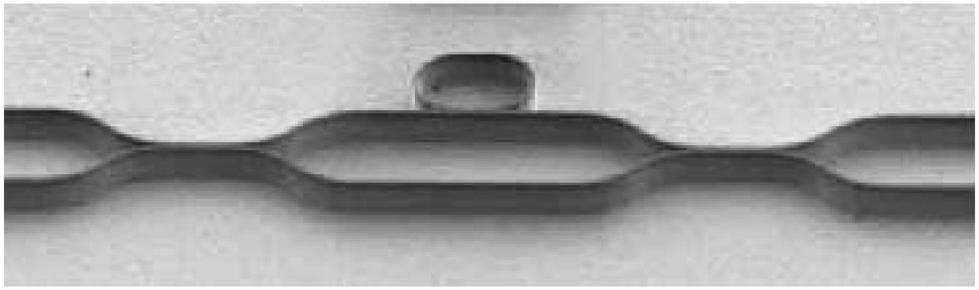


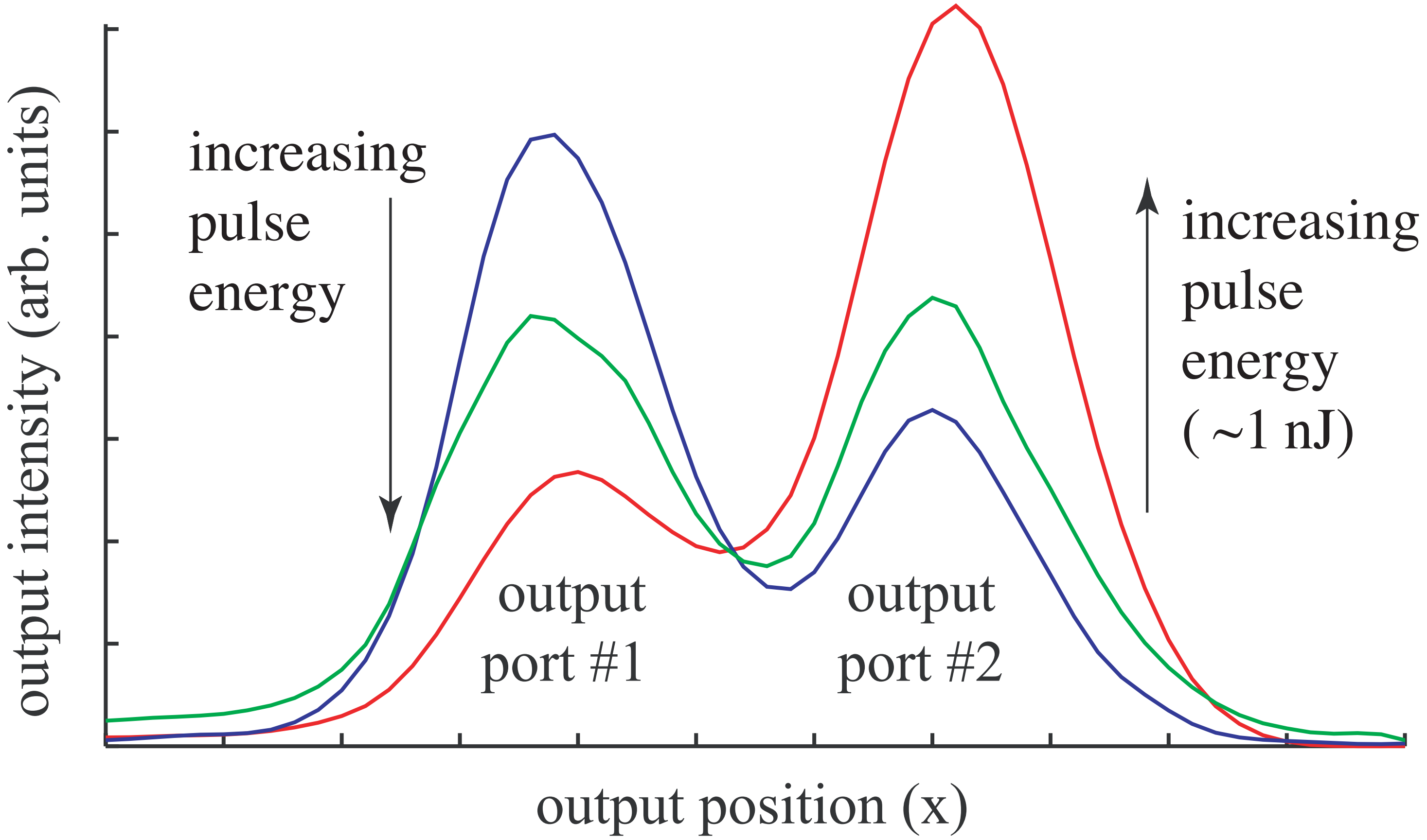
induced phase shift



# All-Optical Switching in a Microresonator-Enhanced Mach-Zehnder Interferometer







# Summary

Demonstration of room temperature superluminal propagation in alexandrite and slow light in ruby

Observation of the quantum signature of coincidence imaging and demonstration of position-momentum EPR paradox

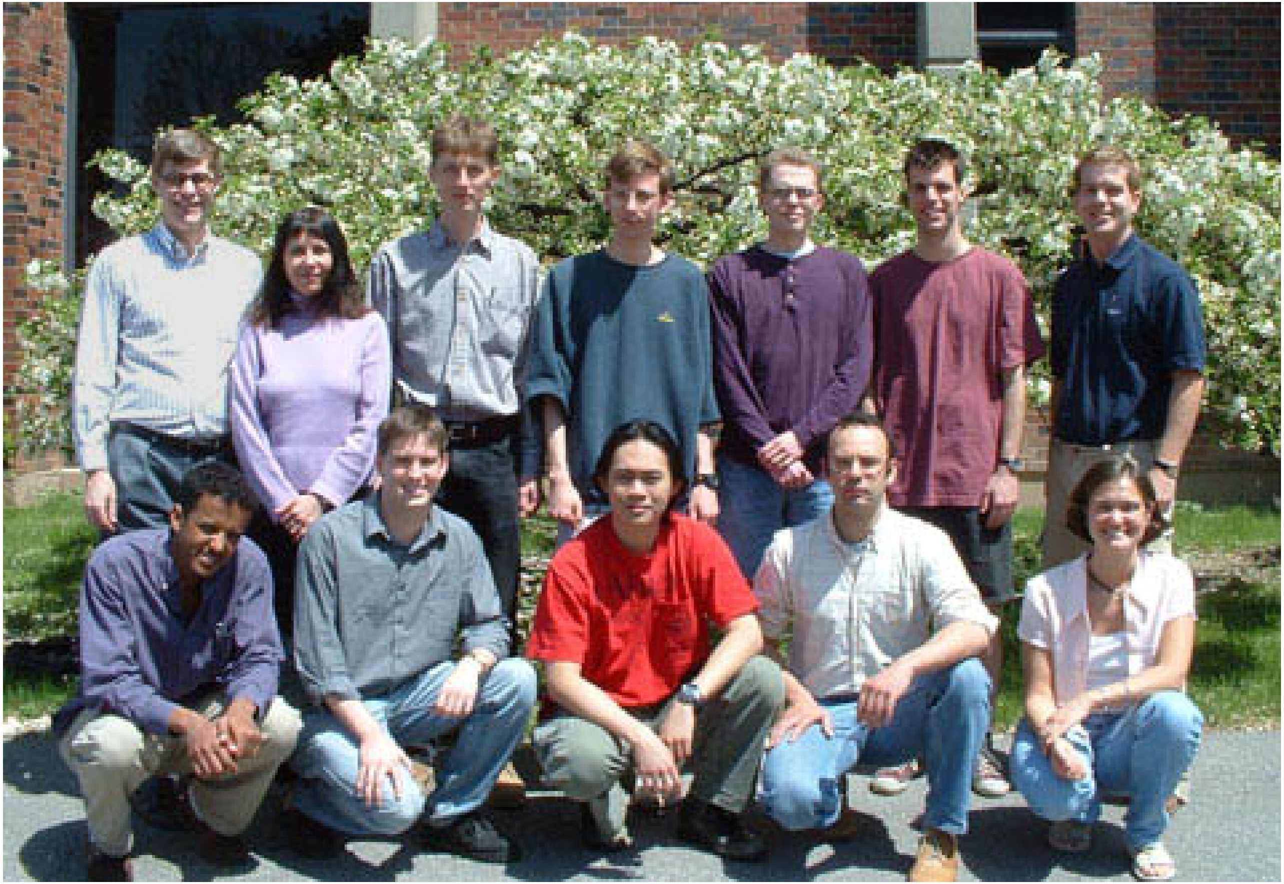
Artificial materials hold great promise for applications in photonics because of

- large controllable nonlinear response
- large dispersion controllable in magnitude and sign

# Real Summary

Nonlinear optics is an extremely exciting research area because it includes topics that range from fundamental physics to numerous applications.

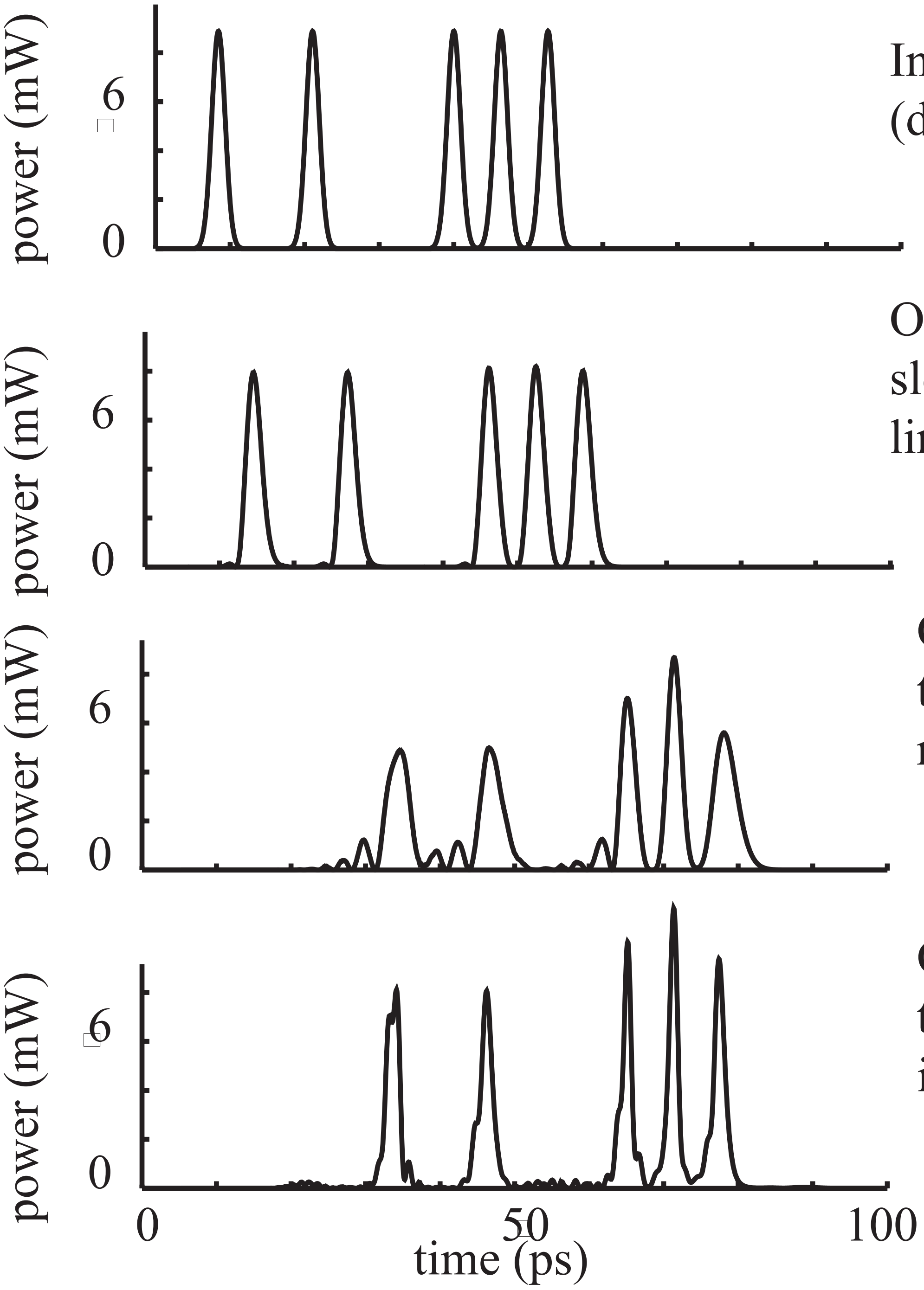
# Special Thanks to my Students and Research Associates



**Thank you for your attention.**

# Photonic Structures --What Next?

# Performance of SCISSOR as Optical Delay Line



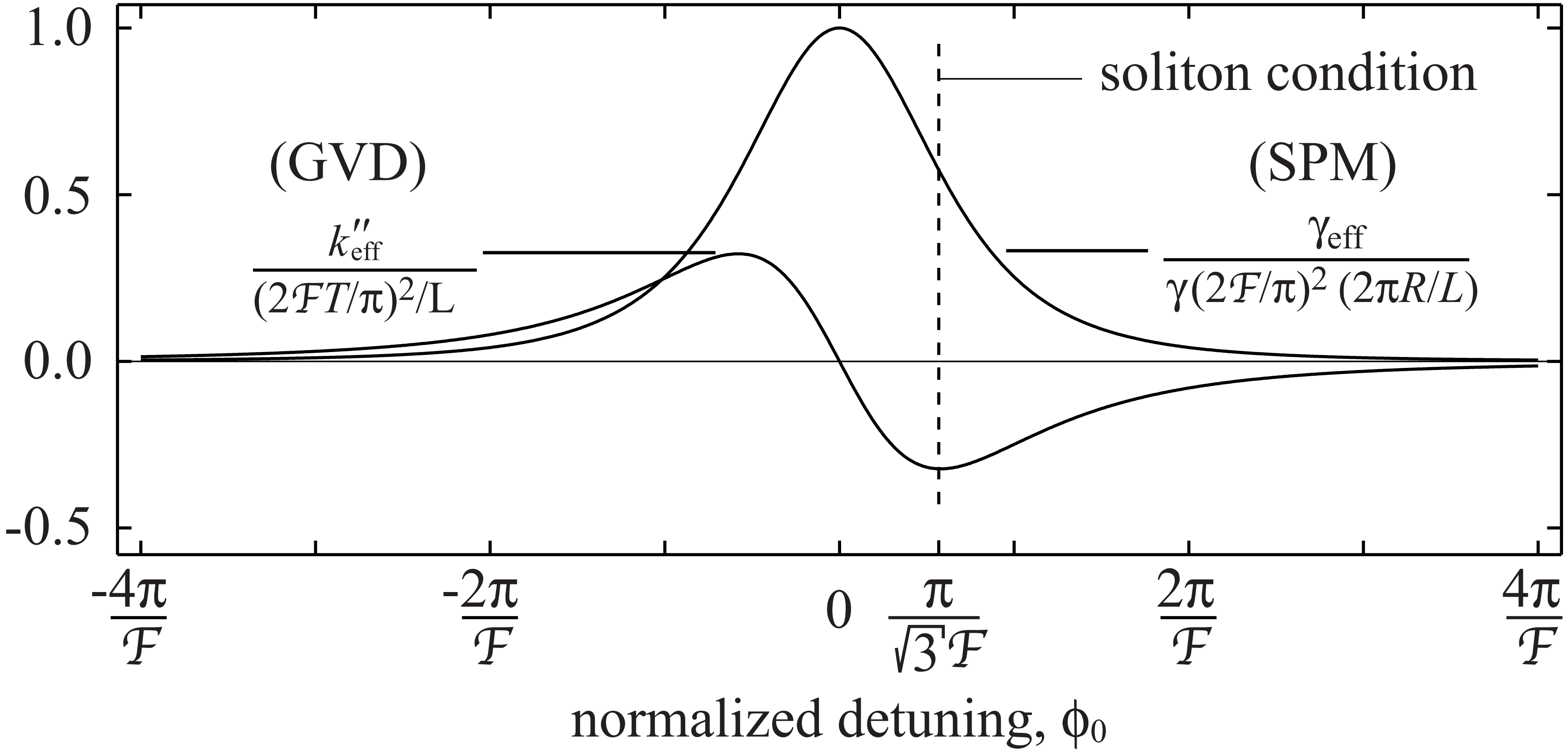
Input
(duty factor = 1/3)

Output --delayed one time slot by six resonators in linear limit

Output --delayed four time slots by 26 resonators in linear limit

Output --delayed four time slots by 26 resonators in nonlinear limit

# Frequency Dependence of GVD and SPM Coefficients



# Soliton Propagation

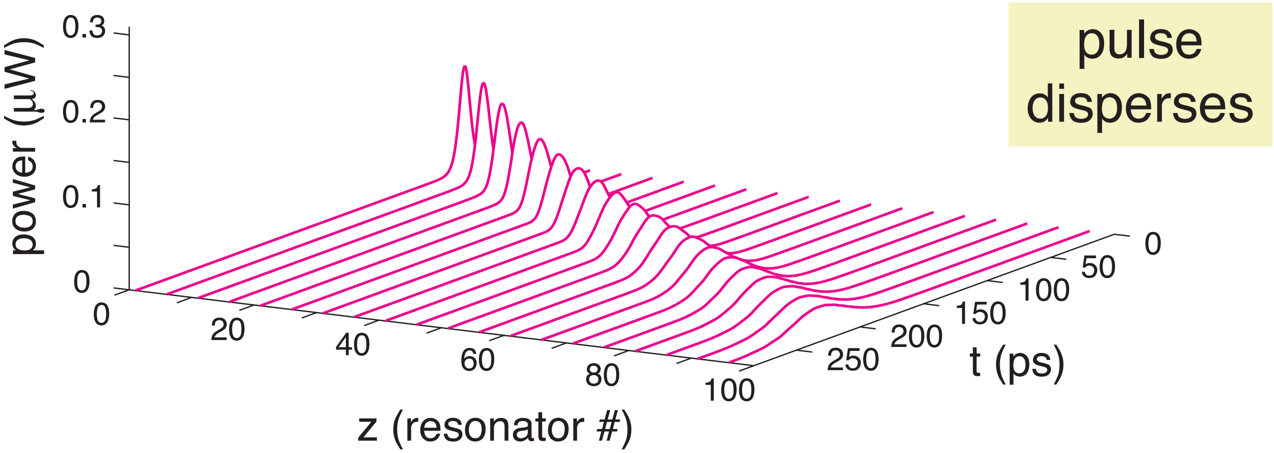
5 $\mu$m diameter resonators with a finesse of 30

SCISSOR may be constructed from 100 resonators spaced by 10 $\mu$m for a total length of 1 mm

soliton may be excited via a 10 ps, 125mW pulse

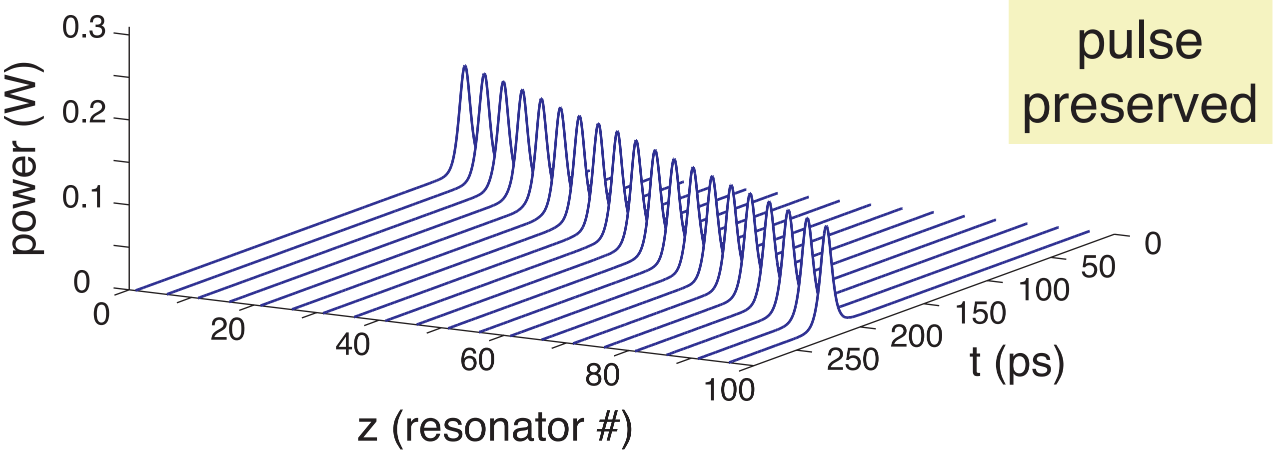
simulation assumes a chalcogenide/GaAs-like nonlinearity

## Weak Pulse



pulse disperses

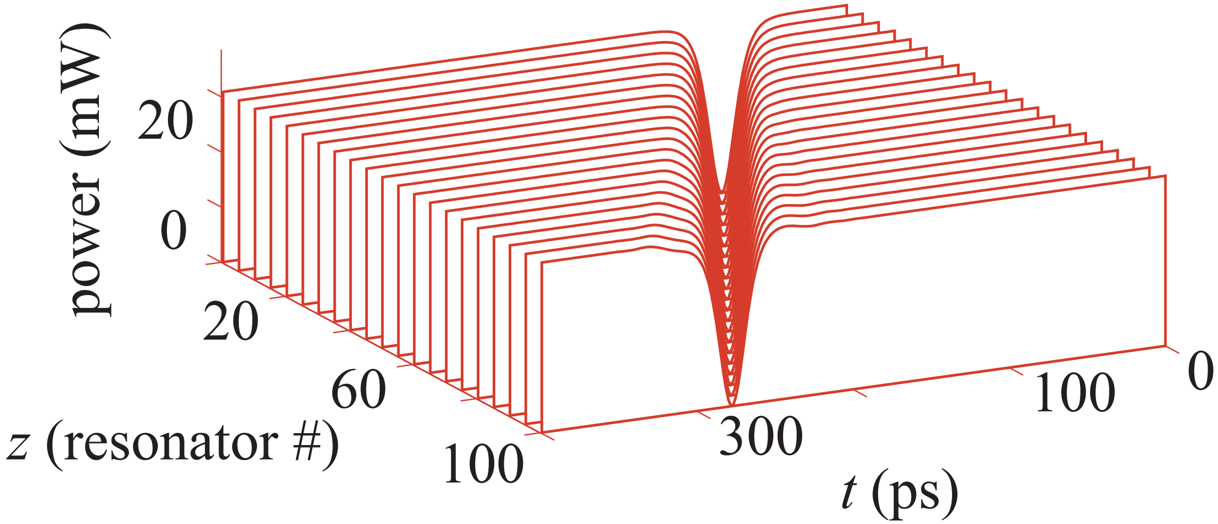
## Fundamental Soliton



pulse preserved

# Dark Solitons

SCISSOR system also supports the propagation of dark solitons.

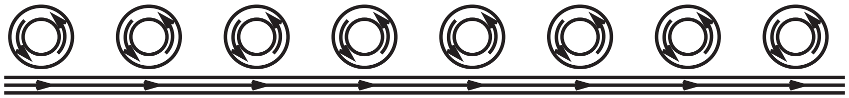


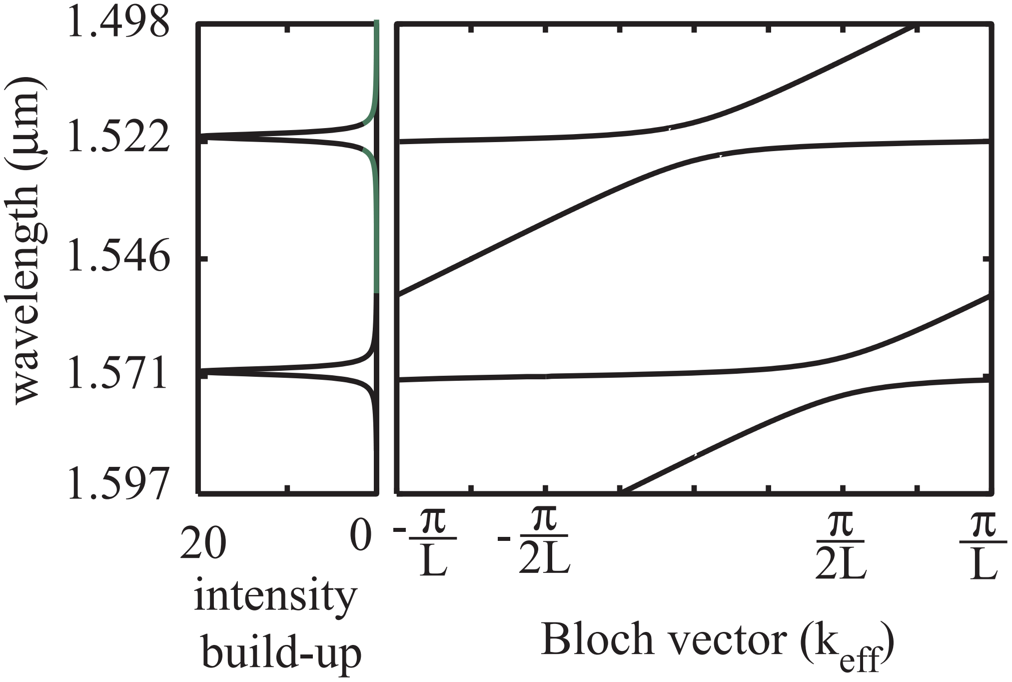
# SCISSOR Dispersion Relations

## Single-Guide SCISSOR

No bandgap

Large intensity buildup

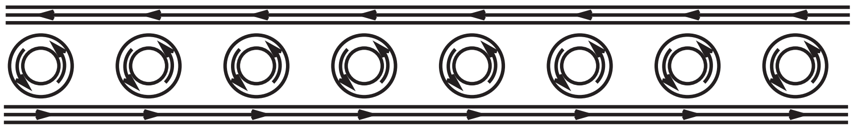


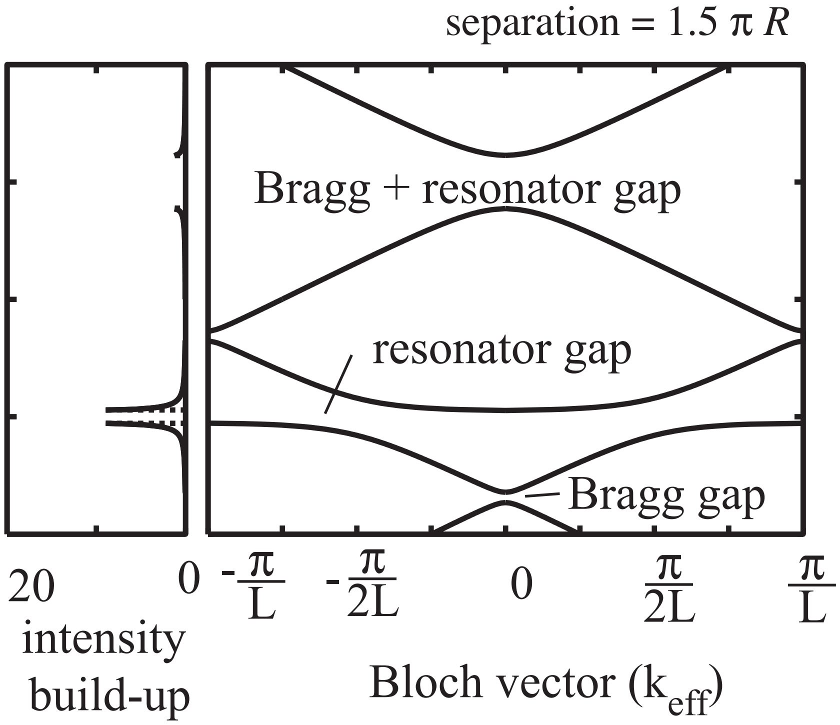


## Double-Guide SCISSOR

Bandgaps occur

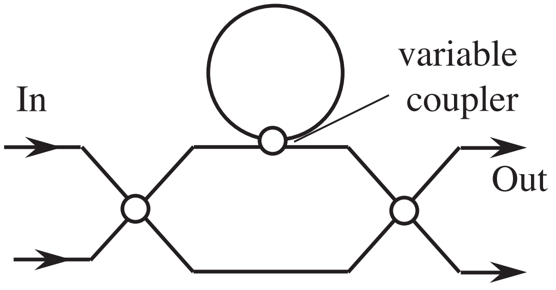
Reduced intensity buildup





# Phase Characteristics of Fiber Ring Resonator

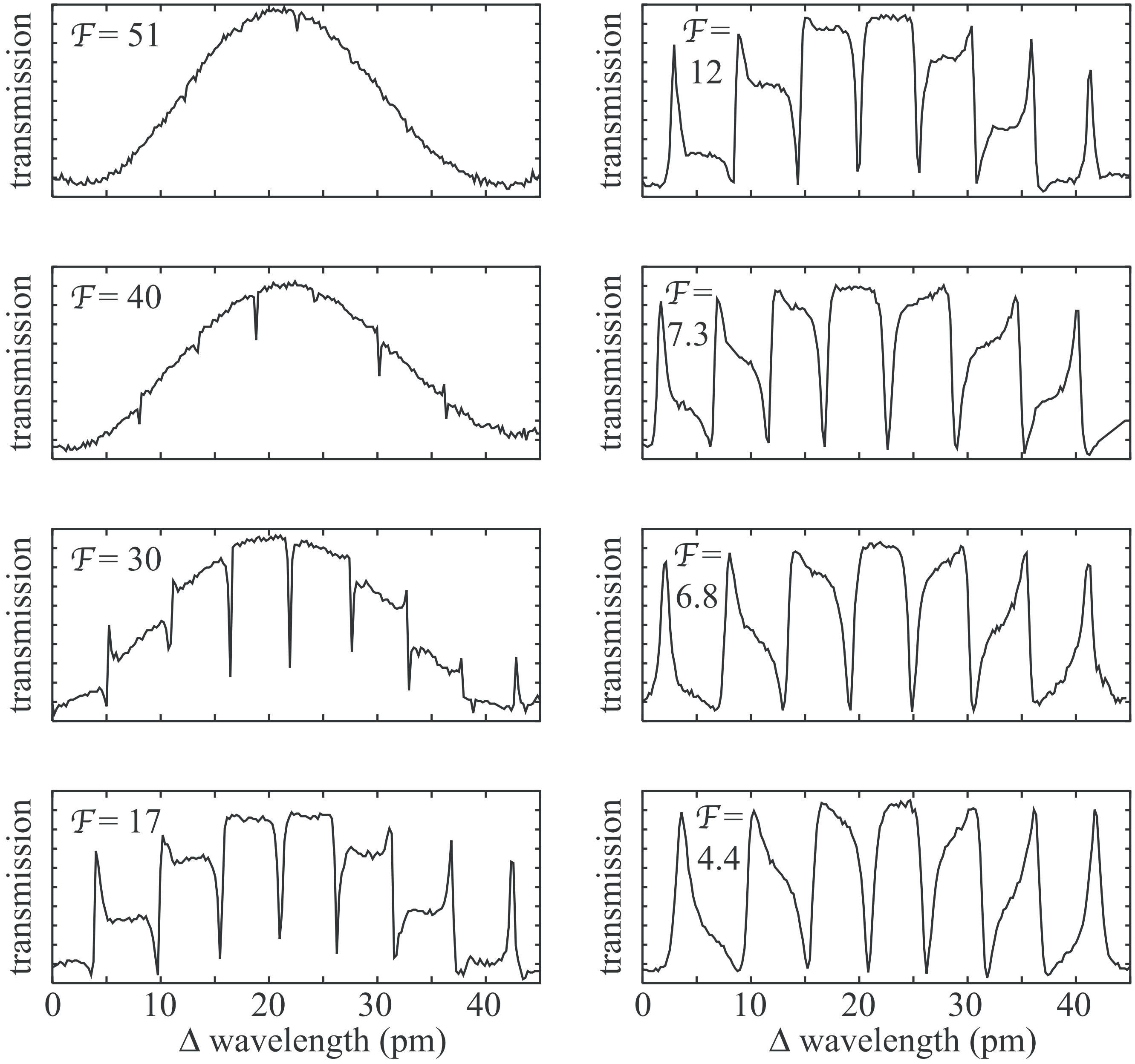
Place ring resonator inside Mach-Zhender interferometer and measure transmission versus wavelength.



undercoupled

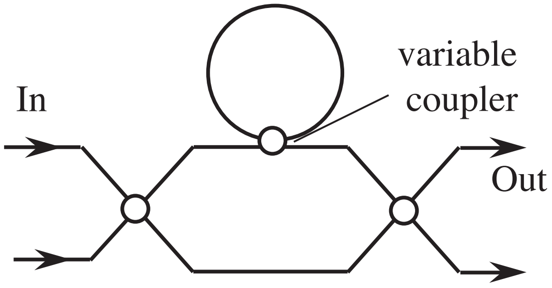
critically coupled

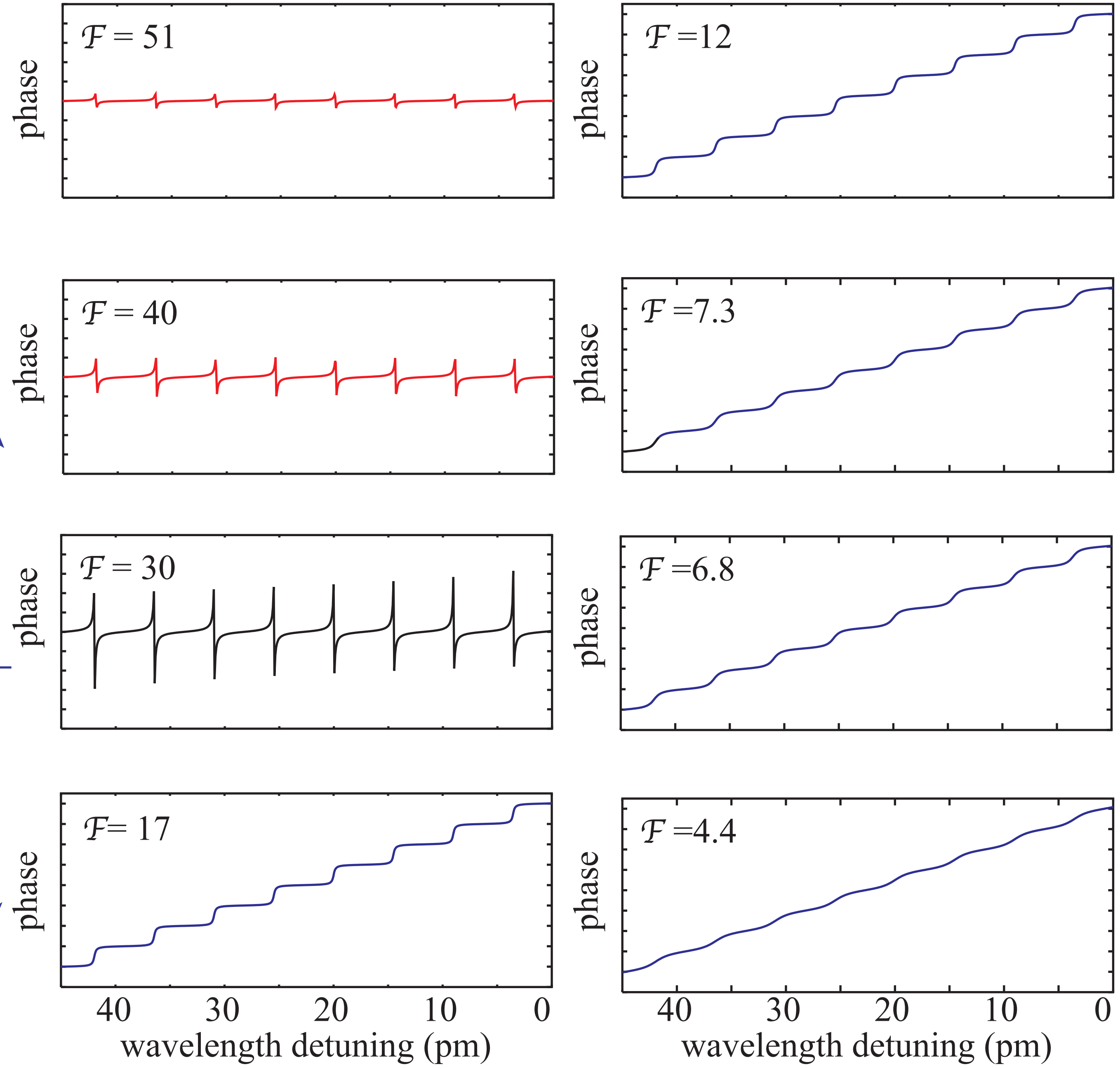
overcoupled



# Phase Characteristics of Fiber Ring Resonator

Extracted phase strcuture





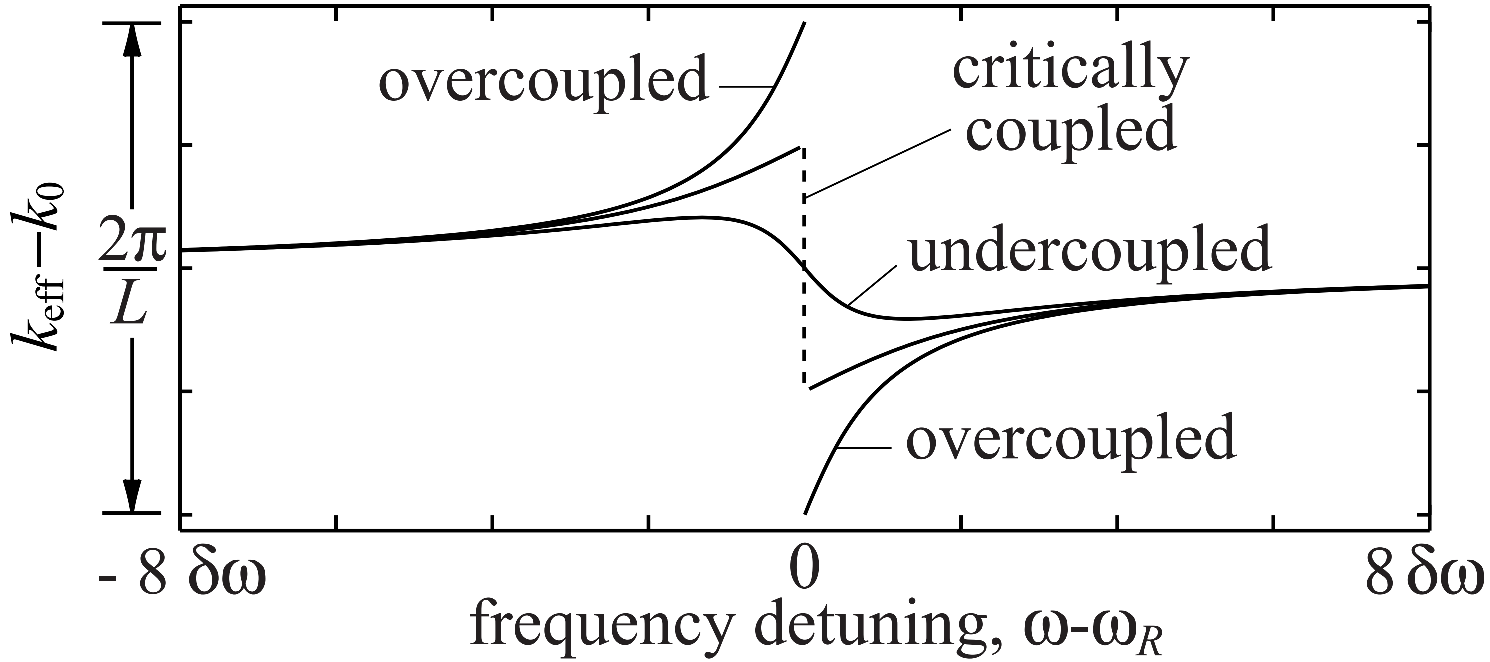
undercoupled

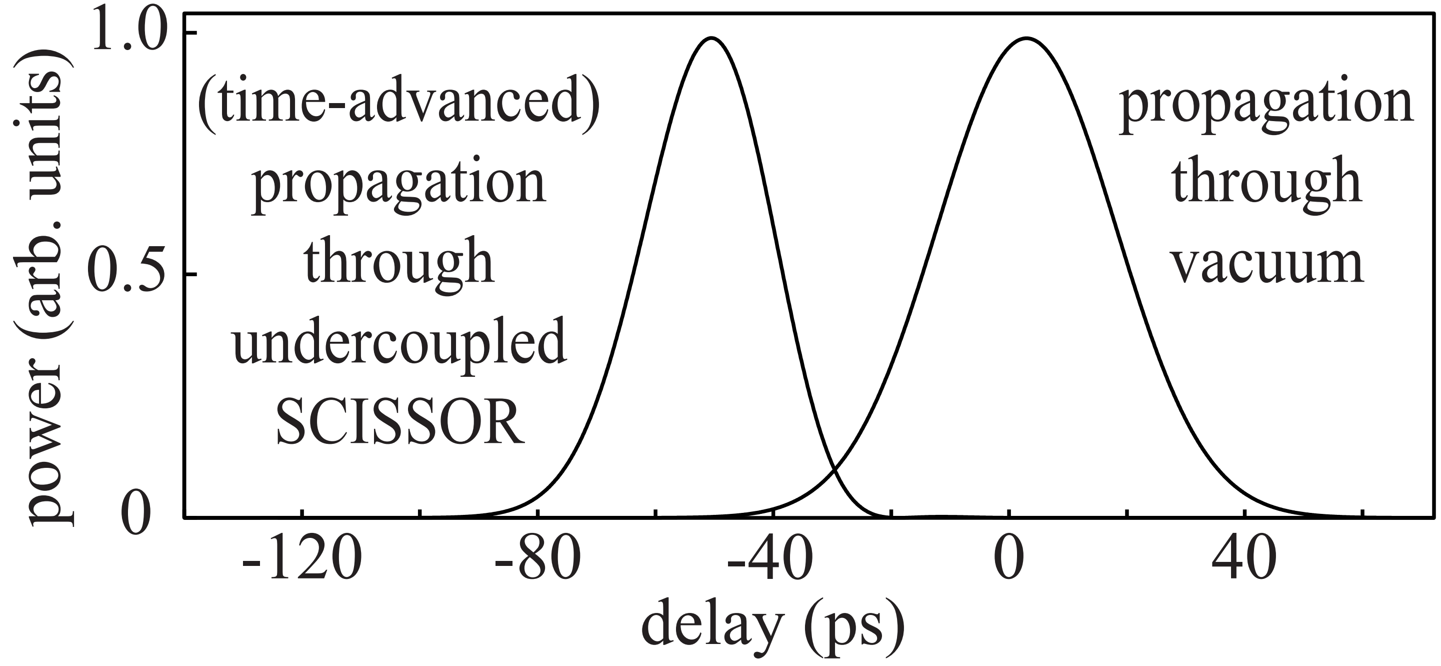
critically coupled

overcoupled

# "Fast" (Superluminal) Light in SCISSOR Structures

Requires **loss** in resonator structure

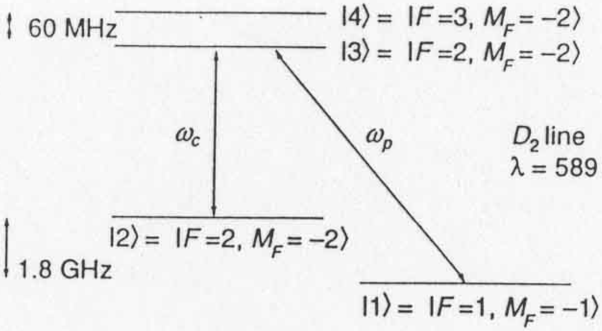




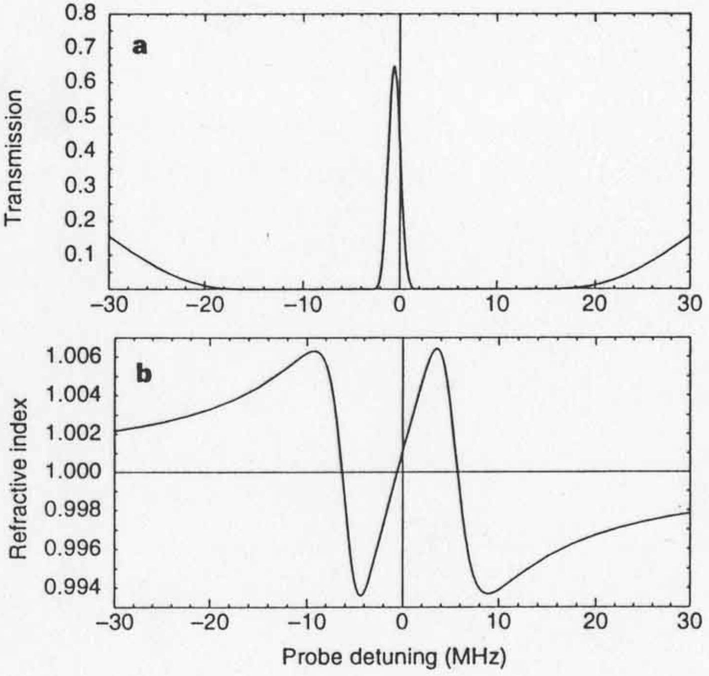
# Light speed reduction to 17 metres per second in an ultracold atomic gas

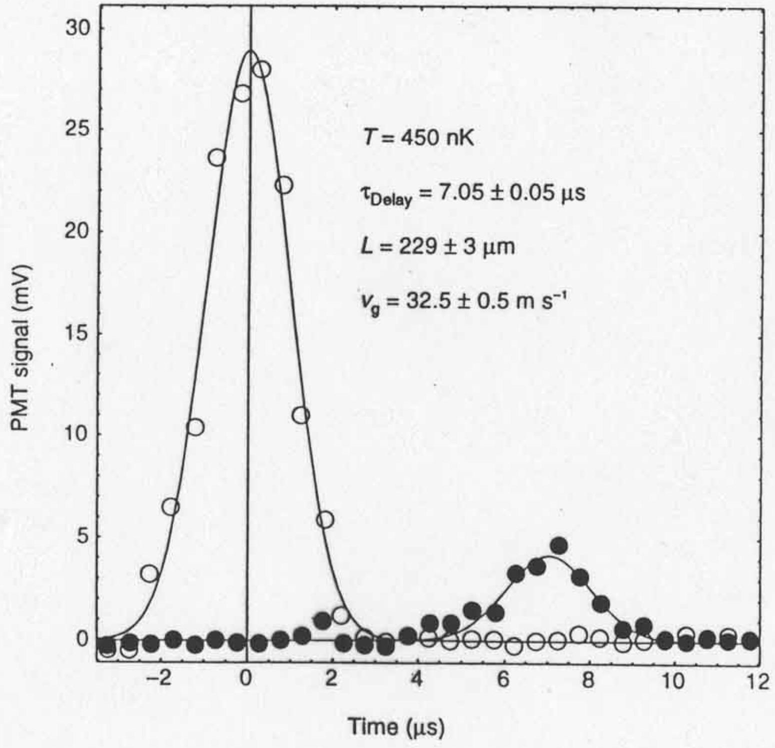
**Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§**

* *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*



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

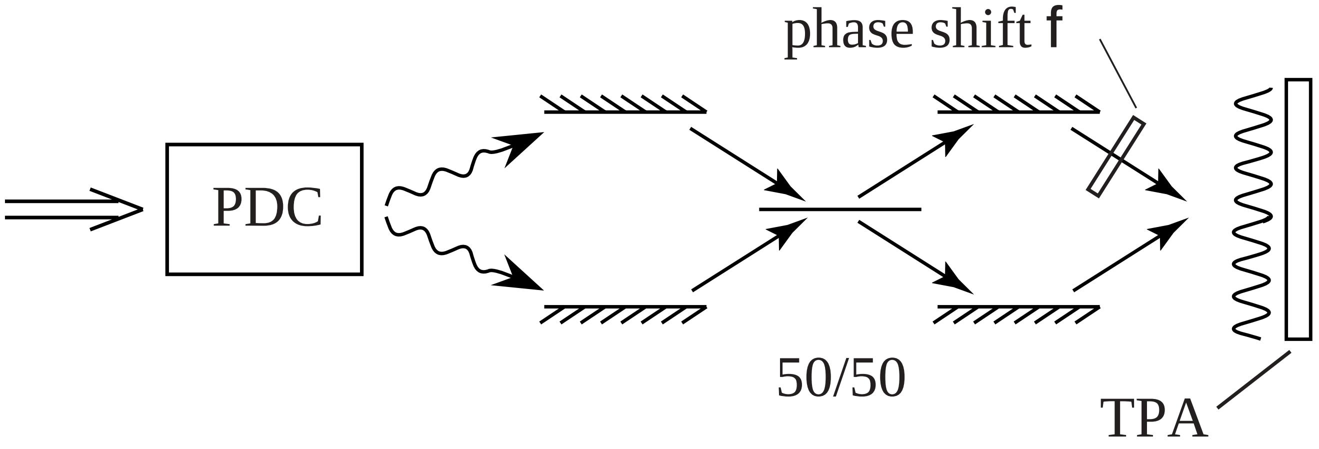




Nature 397, 594 1999

# Quantum Lithography and Microscopy

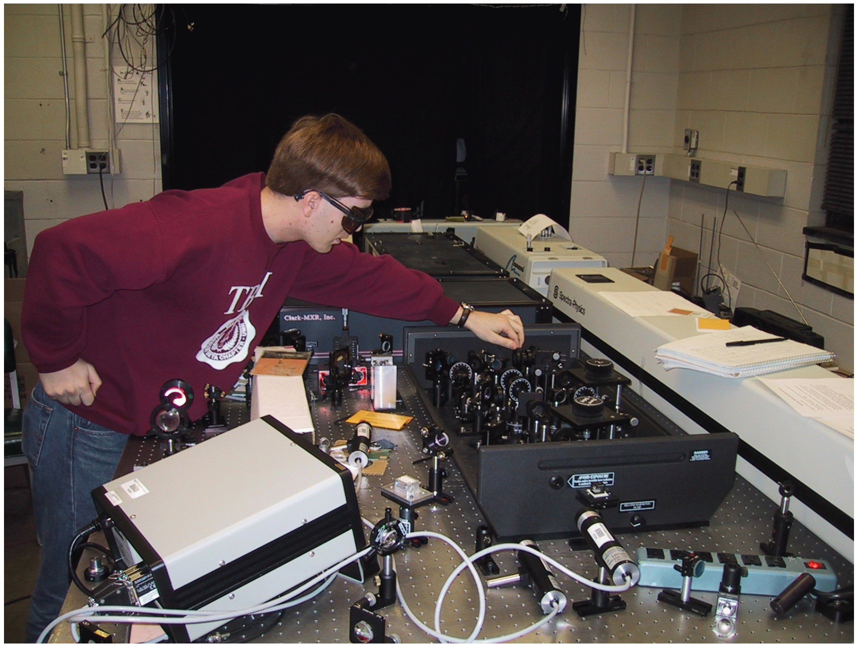
- Entangled photons can be used to form interference patterns with detail finer than the Rayleigh limit
- Process “in reverse” performs sub-Rayleigh microscopy

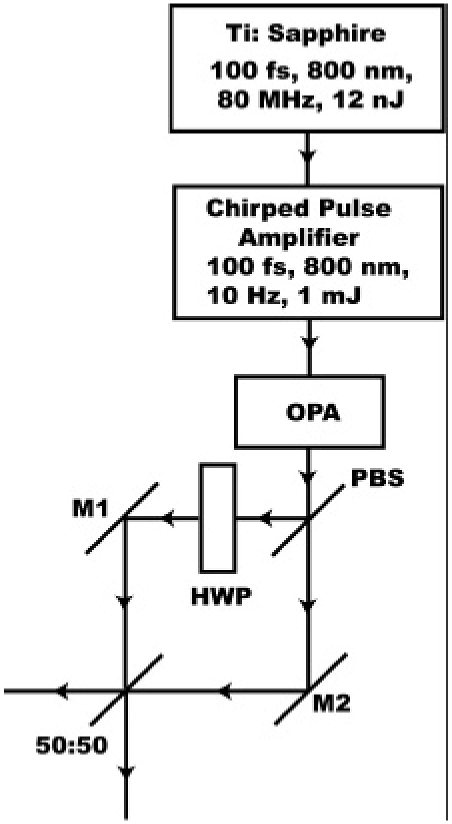


Boto et al, Phys. Rev. Lett. 85, 2733, 2000
Agarwal et al. Phys. Rev. Lett, 86, 1389, 2001.

# QUANTUM LITHOGRAPHY RESEARCH

## Experimental Layout





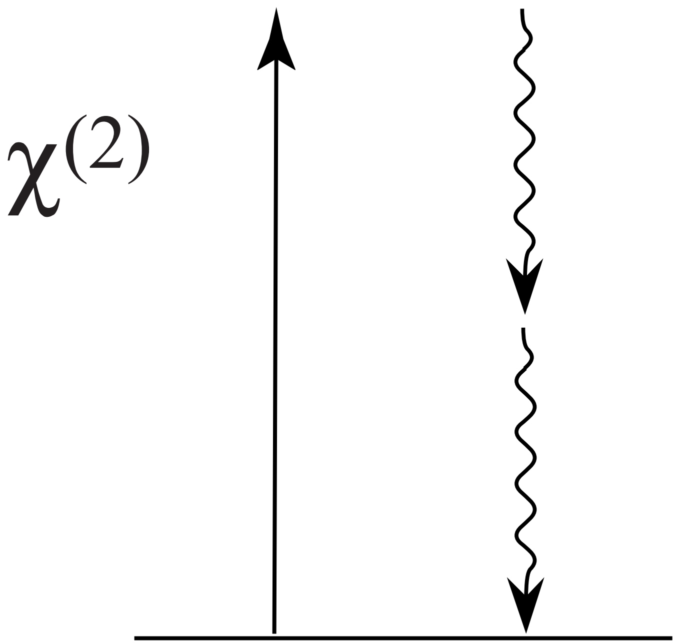
**Ti: Sapphire**
100 fs, 800 nm,
80 MHz, 12 nJ

**Chirped Pulse Amplifier**
100 fs, 800 nm,
10 Hz, 1 mJ

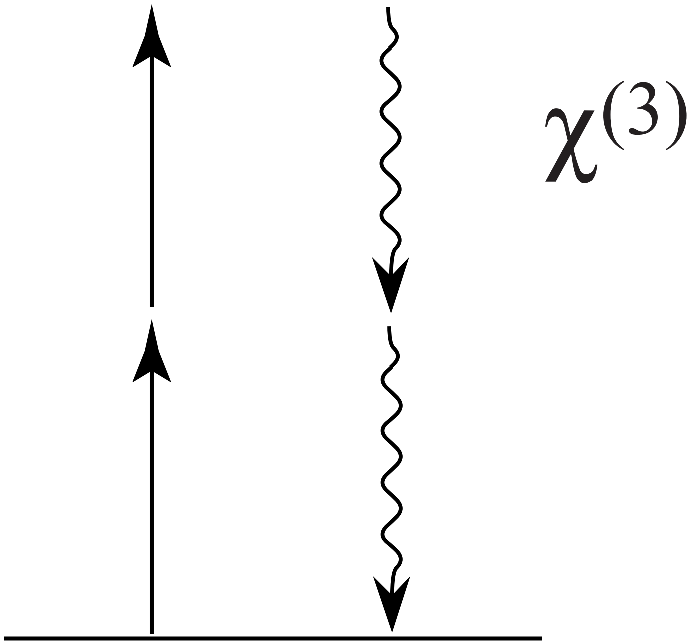
**OPA**

# Implications of Spontaneous Pattern Formation

## Two Routes to Entanglement:

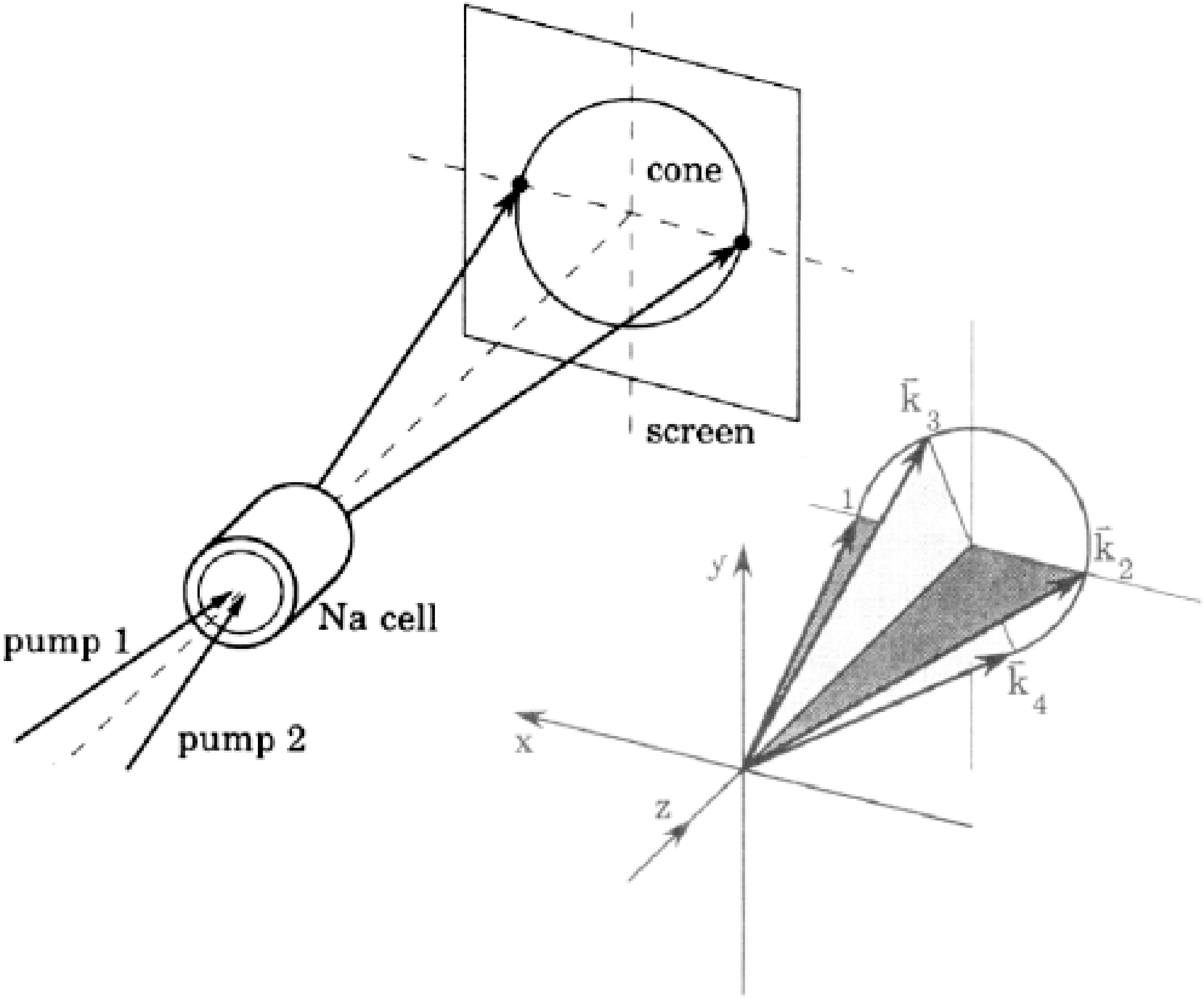


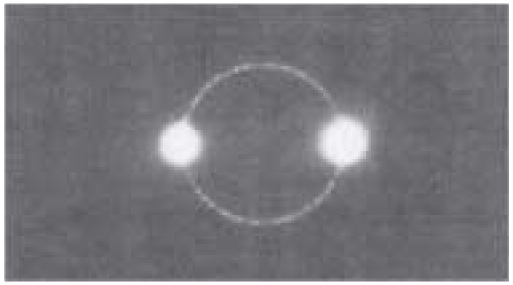
parametric downconversion

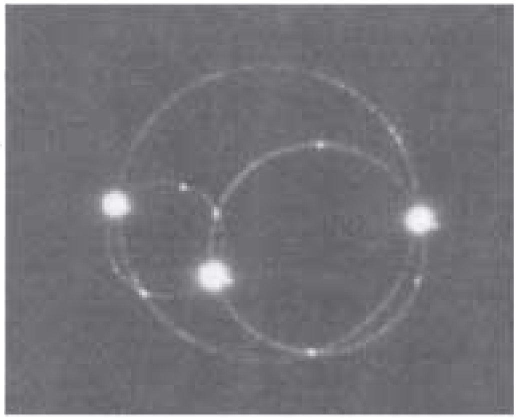


four-wave mixing

# Generation of Quantum States of Light by Two-Beam Excited Conical Emission



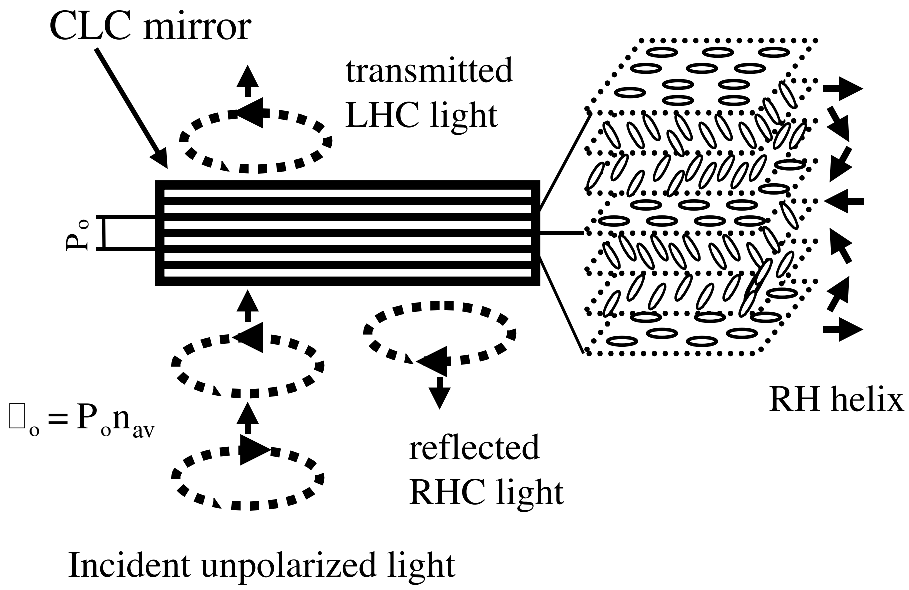




Kauranen et al, Opt. Lett. 16, 943, 1991;  Kauranen and Boyd, Phys. Rev. A, 47, 4297, 1993.

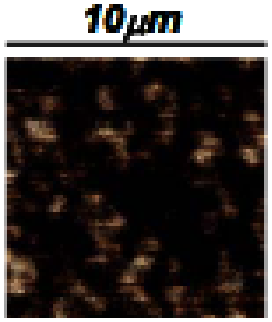
# Source of Polarized, Single-Photons on Demand

- Useful for secure communication by quantum cryptgraphy
- Embed isolated dye molecules in chiral nematic liquid crystal
- Host acts as self-assembled photonic bandgap material
- Host composition helps prevent dye from bleaching
- Fluorescence shows strong antibunching

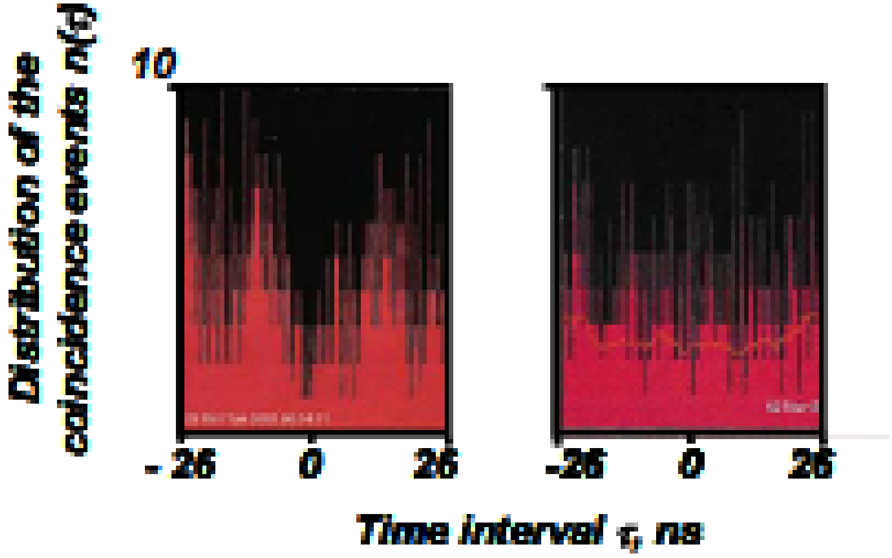


Experimental procedure. Terrylene dye molecules are doped into a polymer cholesteric iquid crystal host.

S. Lukishova, A. Schmid, C. Stroud, RWB



Confocal fluorescence micrograph



Brown Twiss intensity correlations