Nonlinear Optical Physics
especially
"Slow" and "Fast" Light in
Room-Temperature Solids

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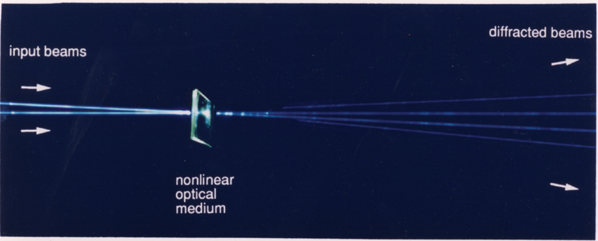
The Essence of Nonlinear Optics

Light-By-Light Scattering



Interest in Slow Light

Fundamentals of optical physics

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

Optical delay lines, optical storage, optical memories

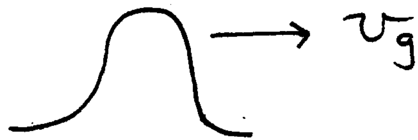
Implications for quantum information

Slow Light

group velocity $\neq$ phase velocity

Group Velocity

Pulse
(wave packet)



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

For $\quad k = \dfrac{n\omega}{c} \qquad \dfrac{dk}{d\omega} = \dfrac{1}{c}\left(n + \omega \dfrac{dn}{d\omega}\right)$

Thus

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

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

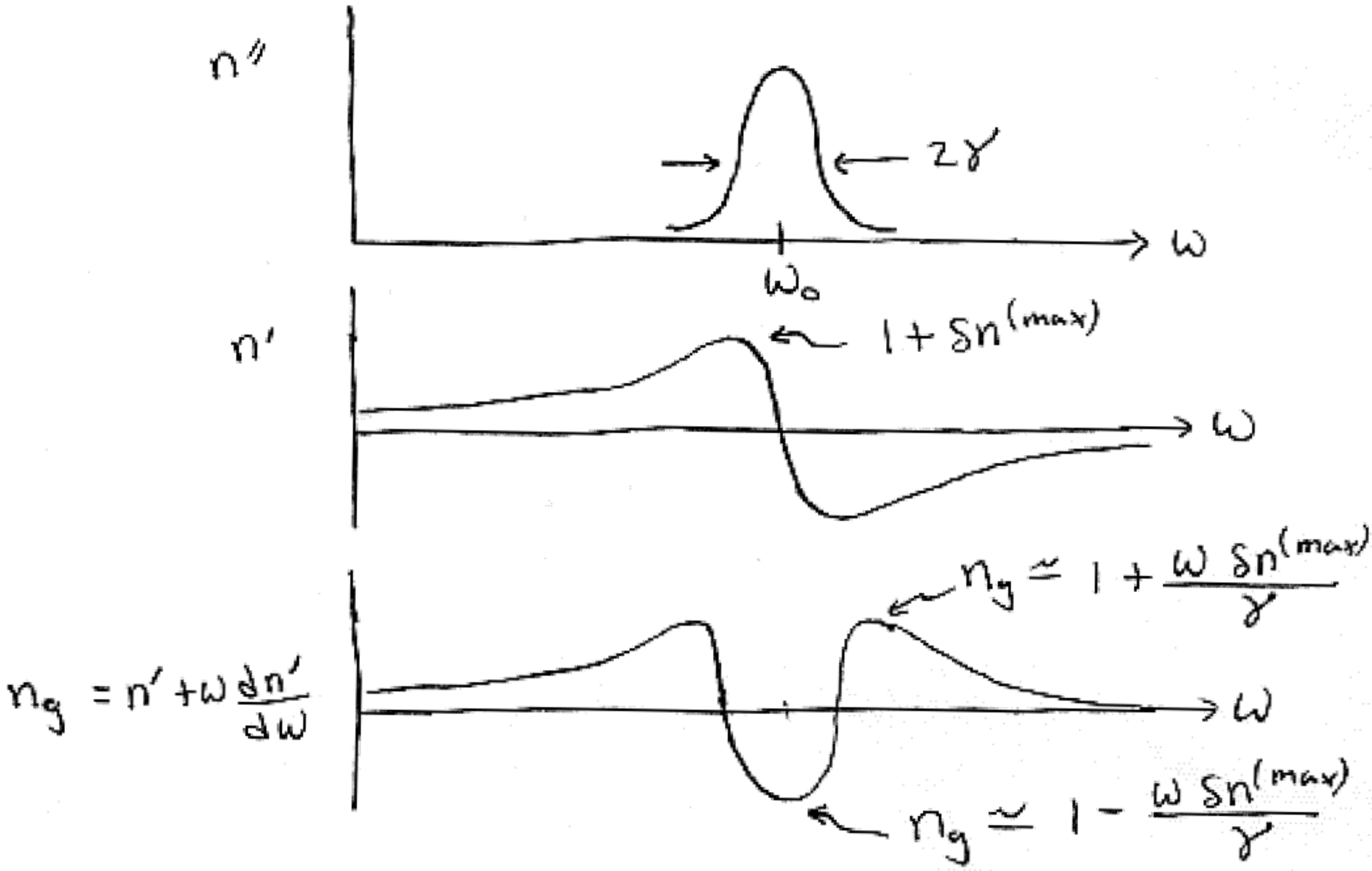
Light Propagation in Atomic Vapors

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

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

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

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



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

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 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

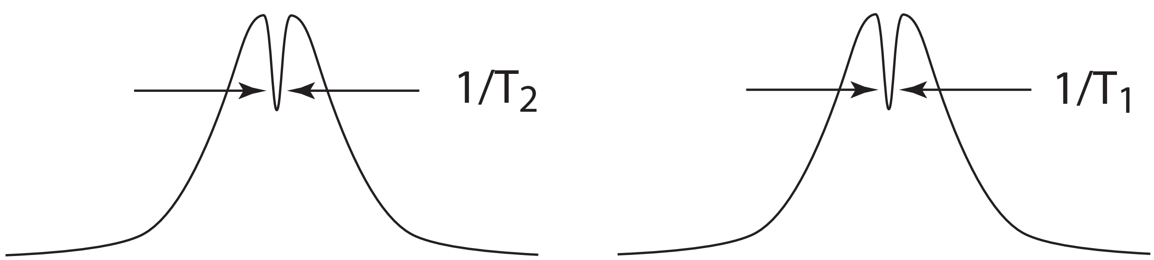
Need a large dn/dω. (How?)

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 $T_2 << T_1$.

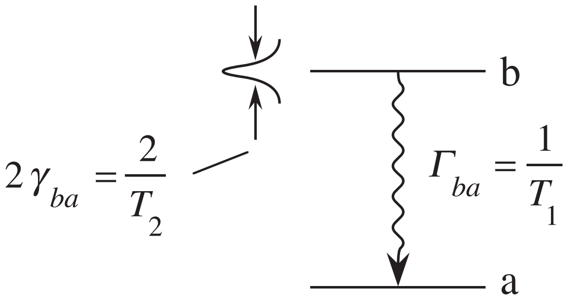


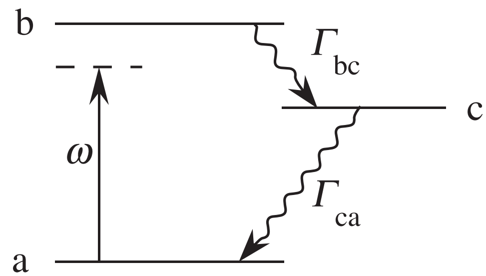
inhomogeneously broadened medium

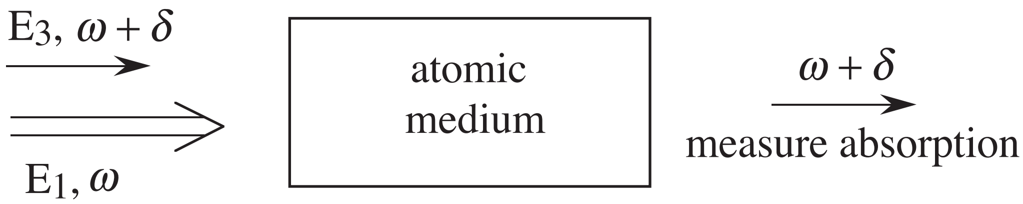
homogeneously broadened medium (or inhomogeneously broadened)

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

Spectral Holes Due to Population Oscillations







Population inversion:

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

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

Probe-beam response:

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

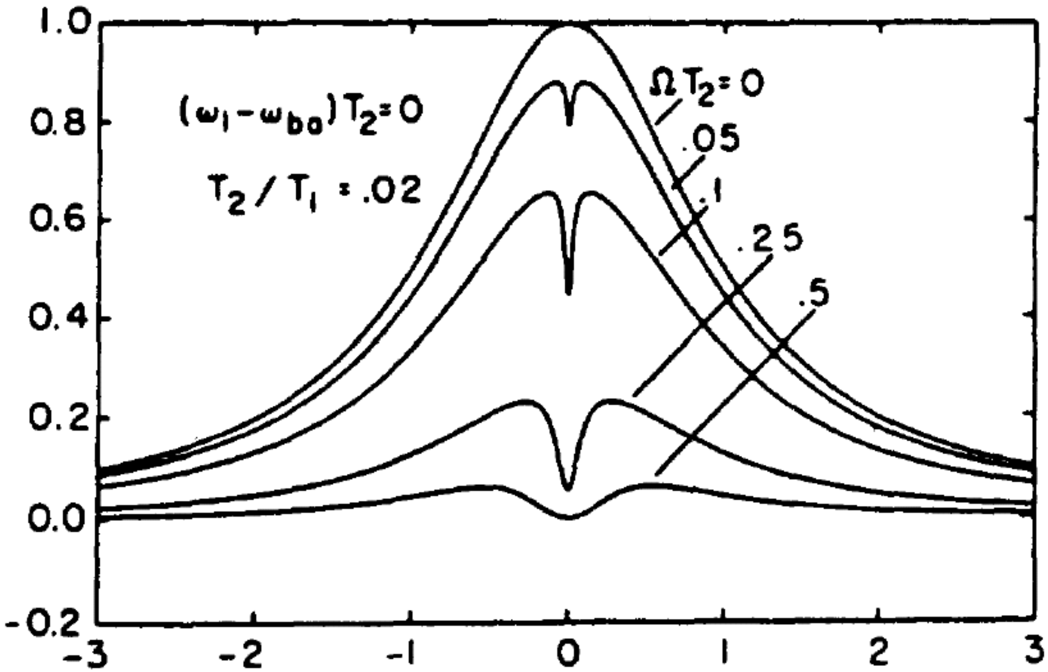
Probe-beam absorption:

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

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

Spectral Holes in Homogeneously Broadened Materials

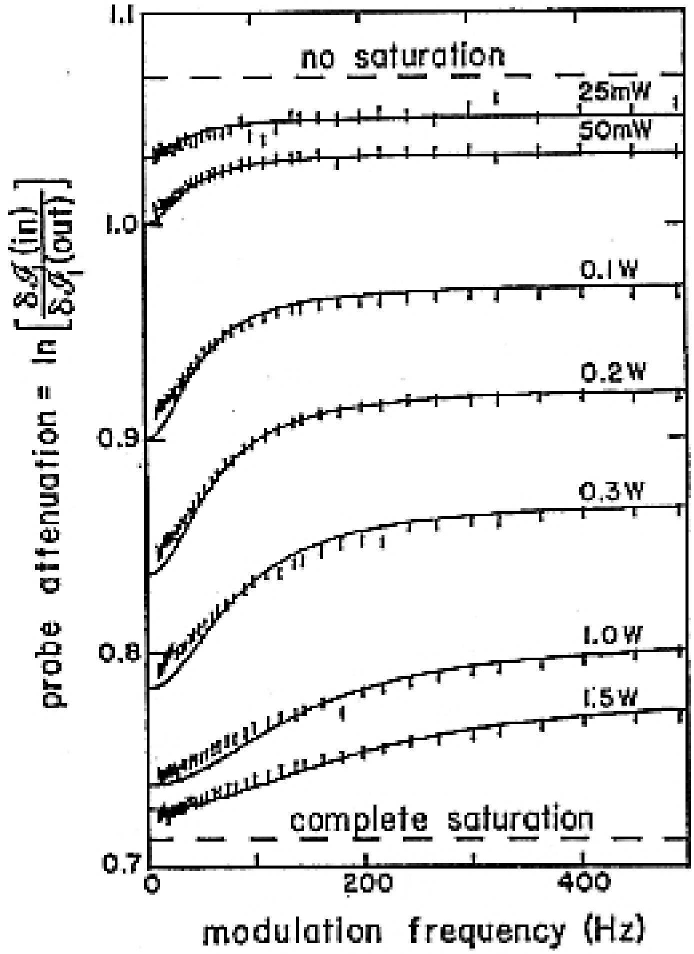
Occurs only in collisionally broadened media ($T_2 << T_1$)



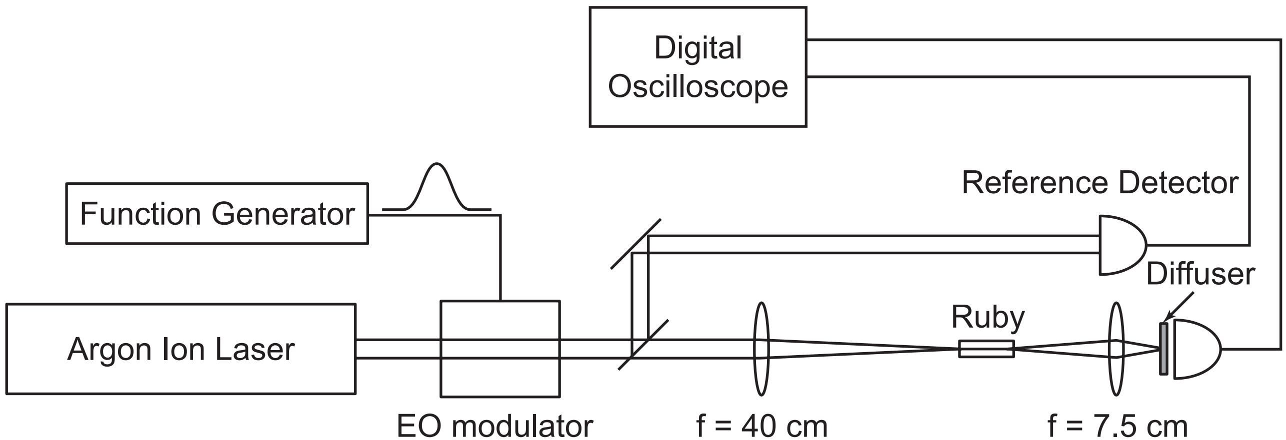
Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

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

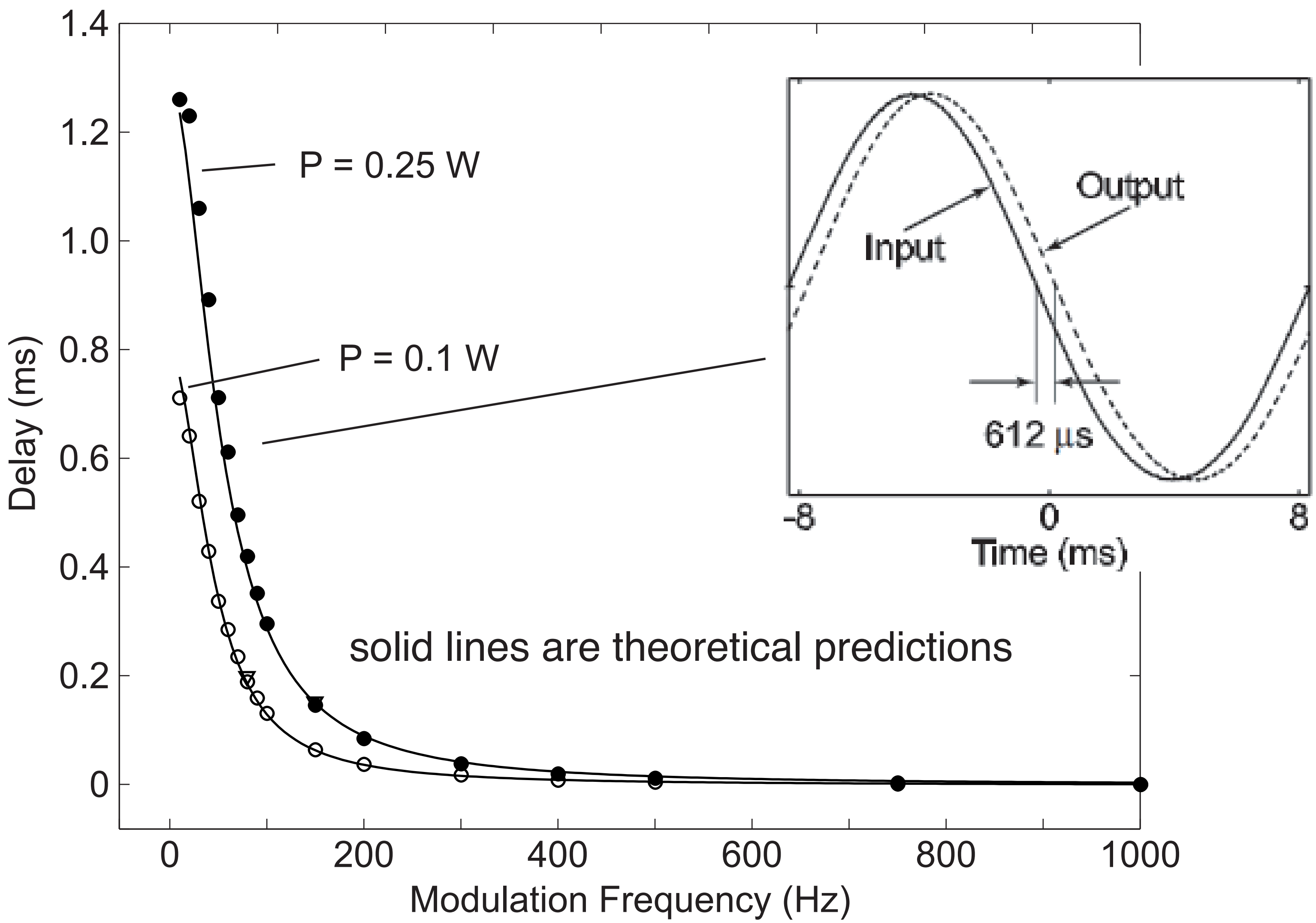


Experimental Setup Used to Observe Slow Light in Ruby



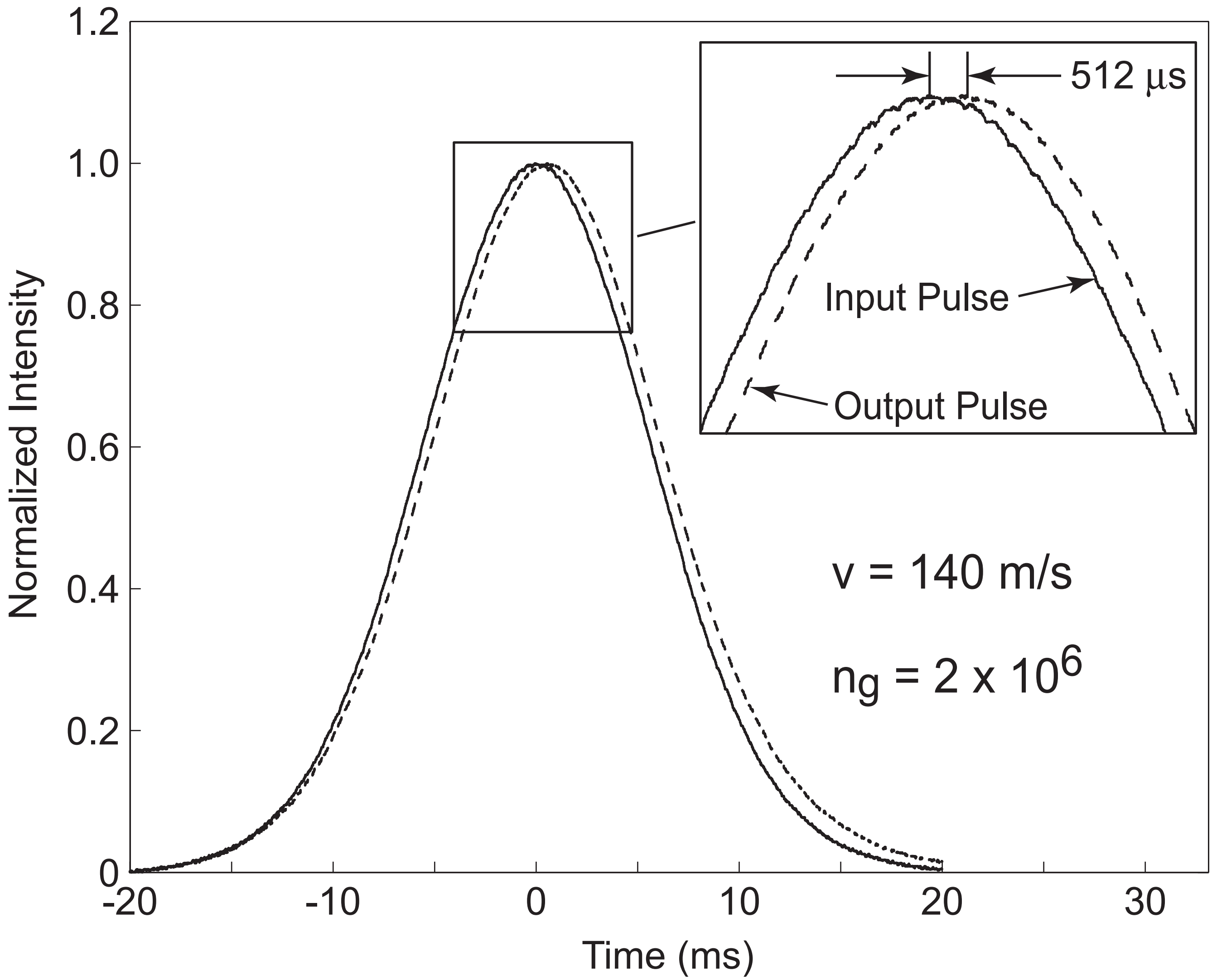
7.25 cm ruby laser rod (pink ruby)

Measurement of Delay Time for Harmonic Modulation



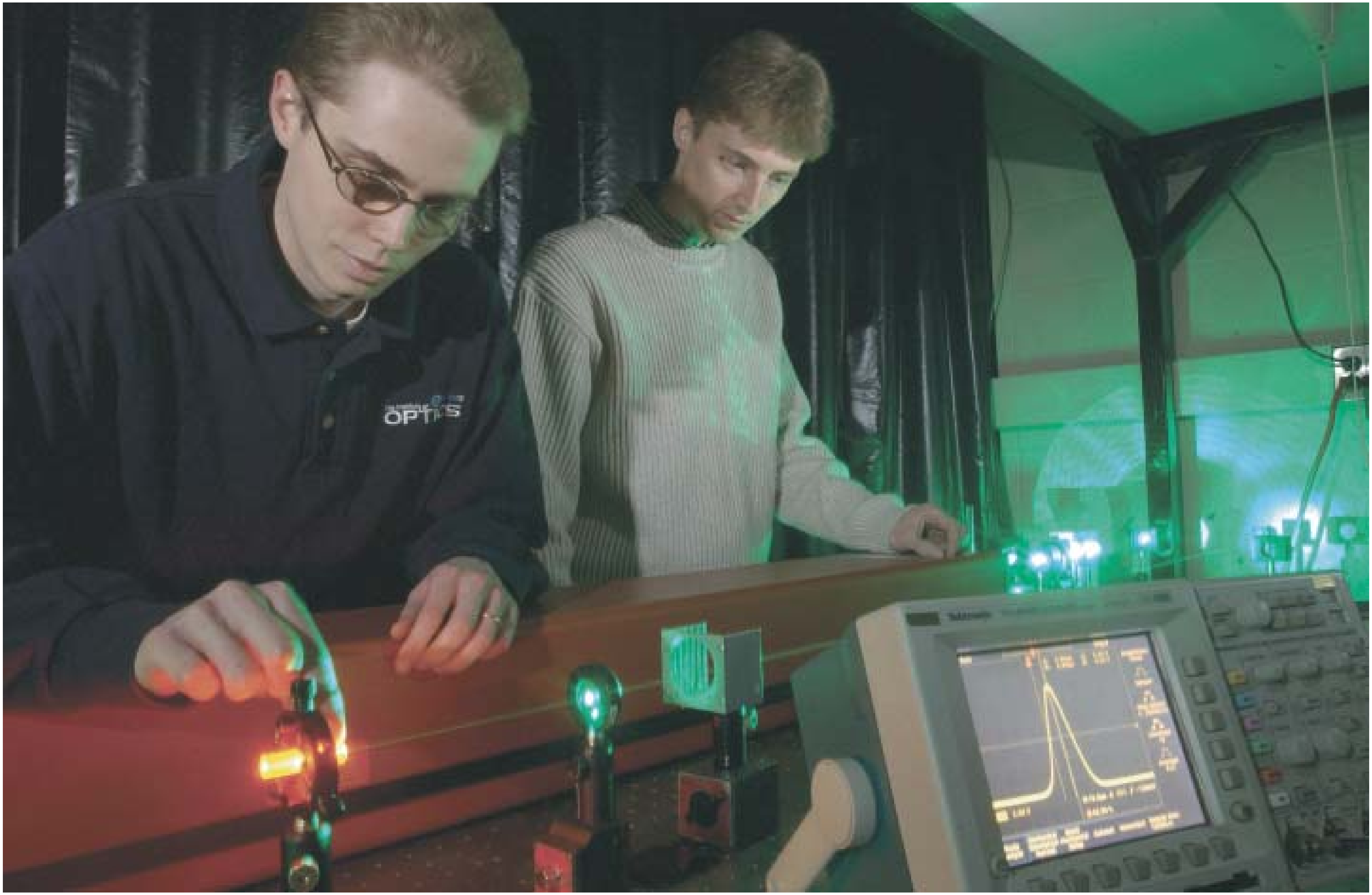
For 1.2 ms delay, v = 60 m/s and $n_g = 5 \times 10^6$

Gaussian Pulse Propagation Through Ruby

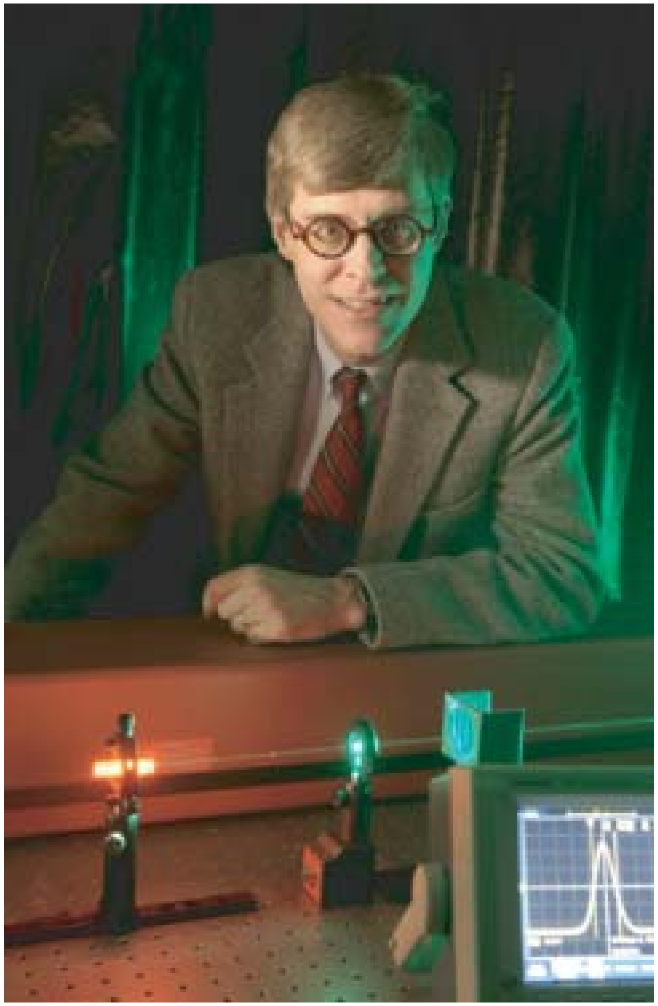


No pulse distortion!

Matt Bigelow and Nick Lepeshkin in the Lab



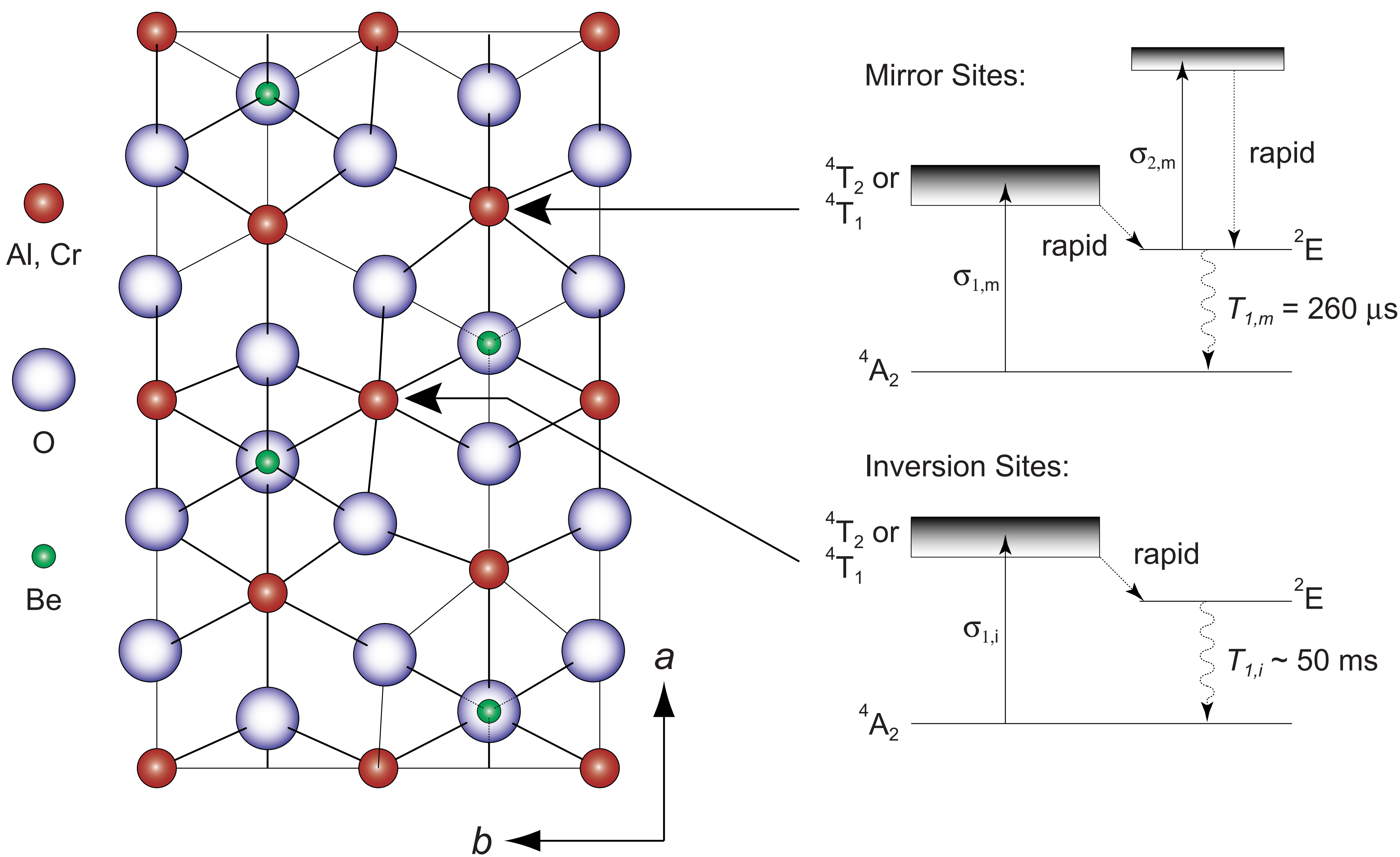
Comparison of University of Rochester and University of Arizona



Bob and Ruby

Hyatt and Galina

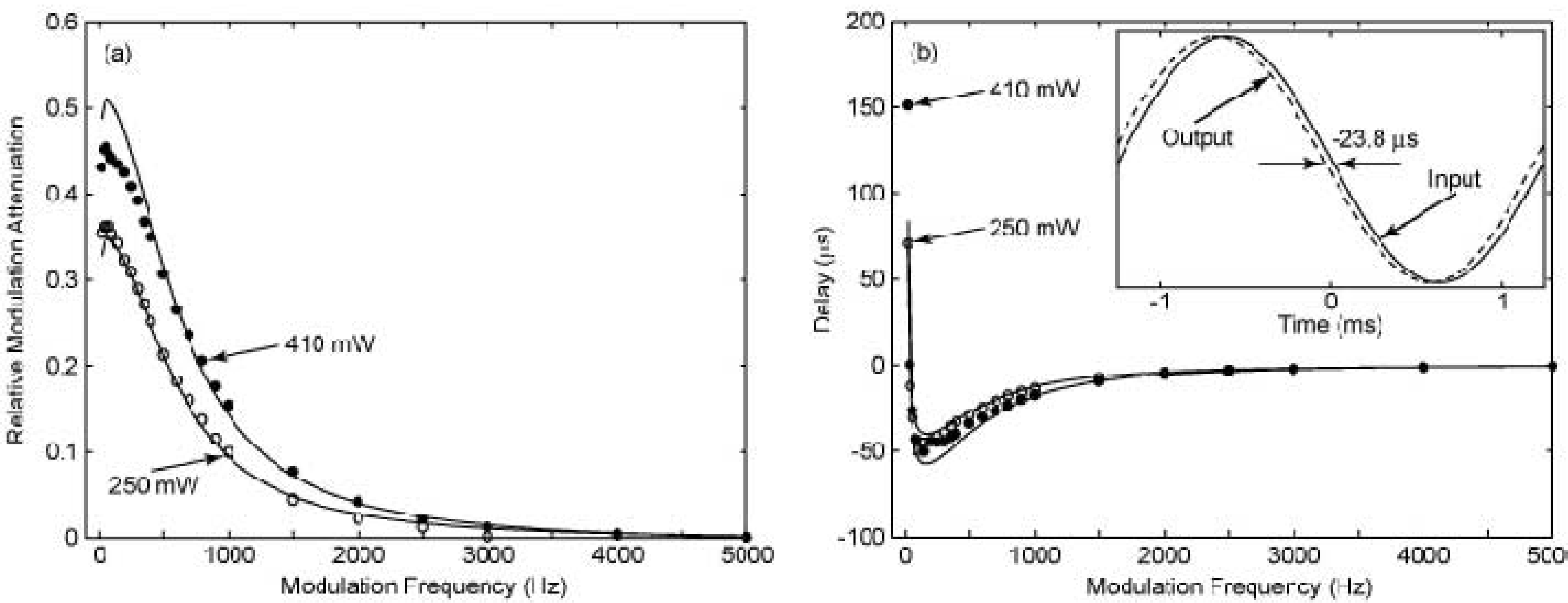
Alexandrite Displays both Saturable and Inverse-Saturable Absorption



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, accepted for publication, 2003

Slow and Fast Light --What Next?

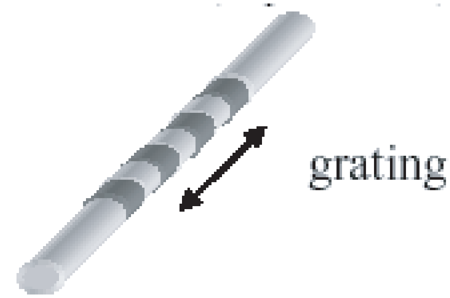
Longer fractional delay
(saturate deeper; propagate farther)

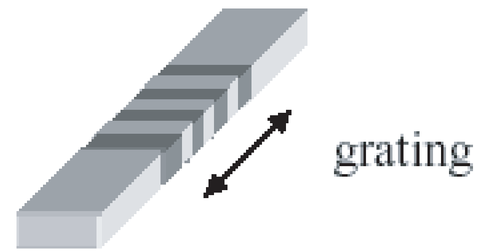
Find material with faster response
(technique works with shorter pulses)

Artificial Materials for Nonlinear Optics

Artifical materials can produce

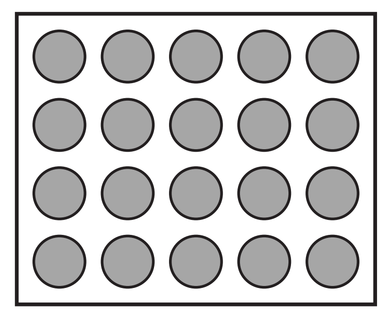
- Large nonlinear optical response
- Large dispersive effects

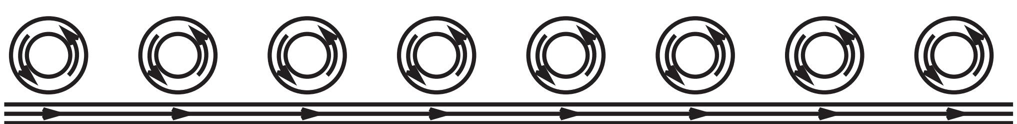




Examples

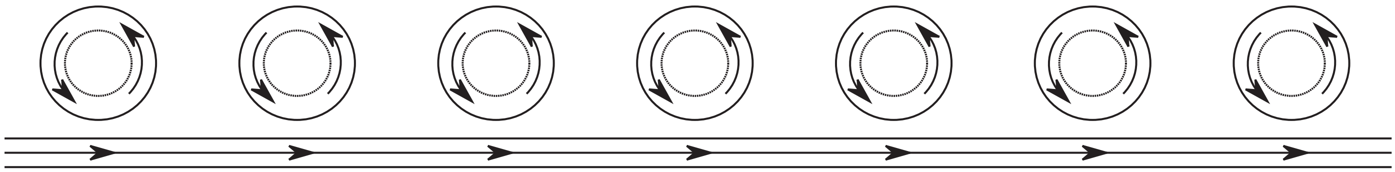
- Fiber/waveguide Bragg gratings
- PBG materials
- CROW devices (Yariv et al.)
- SCISSOR devices





NLO of SCISSOR Devices

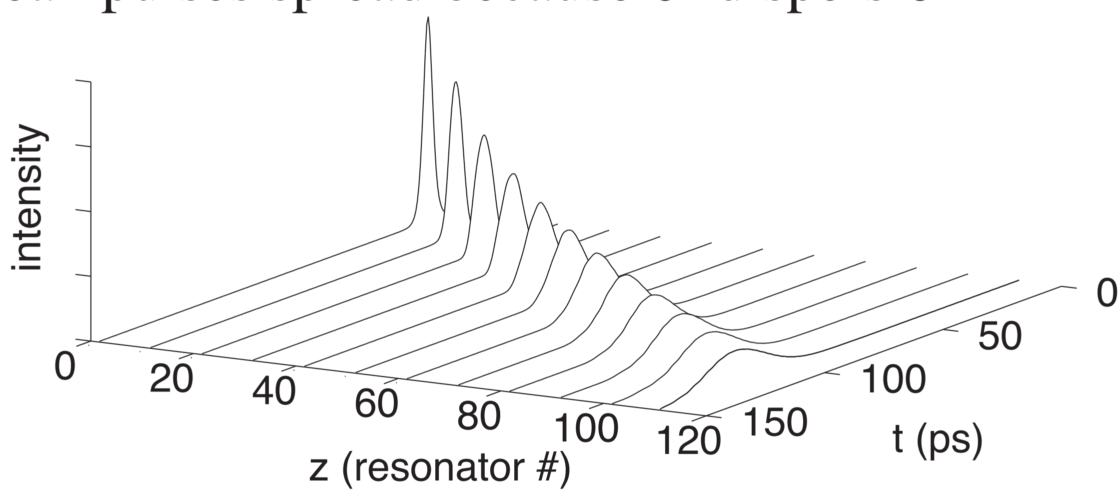
(Side-Coupled Integrated Spaced Sequence of Resonators)



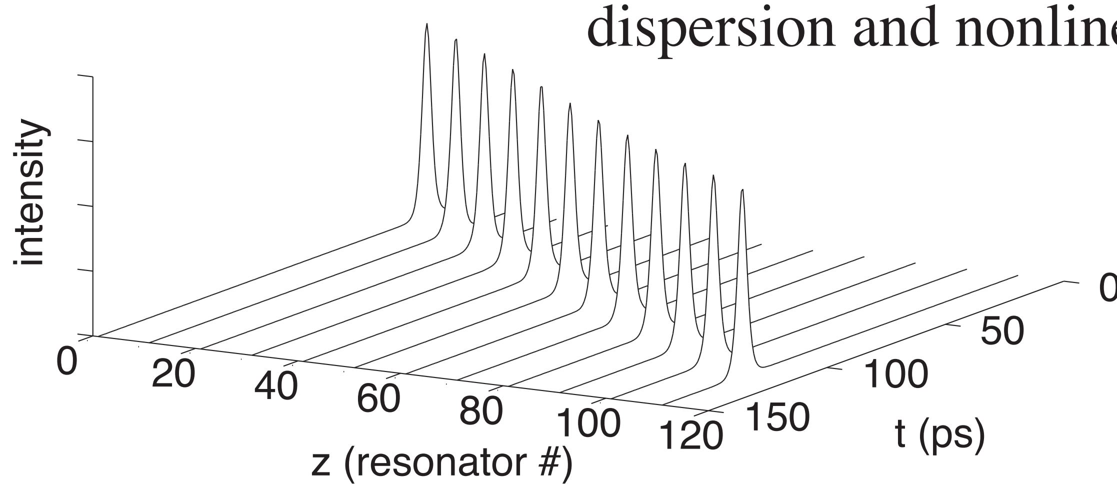
Shows slow-light, tailored dispersion, and enhanced nonlinearity

Optical solitons described by nonlinear Schrodinger equation

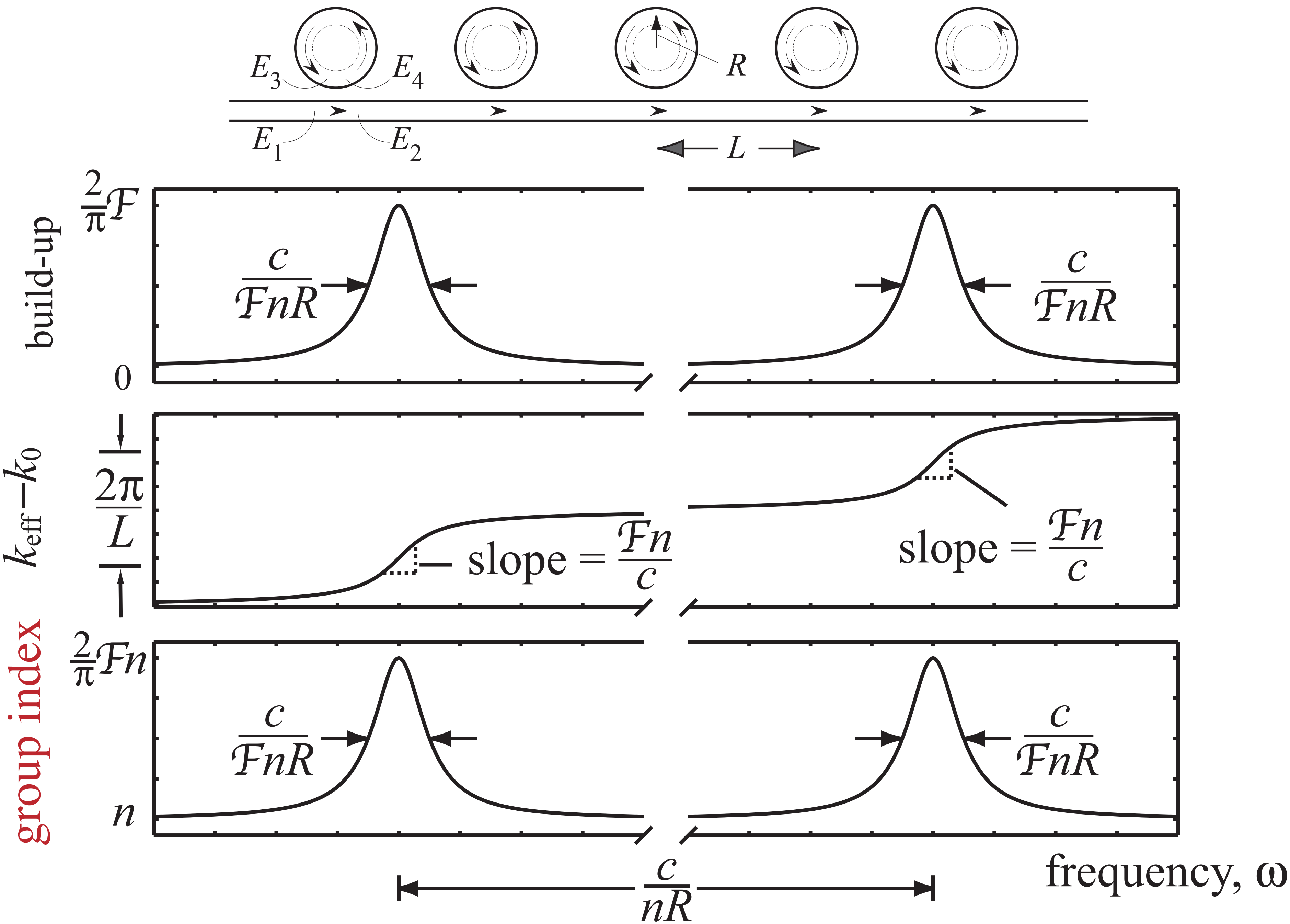
- Weak pulses spread because of dispersion



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

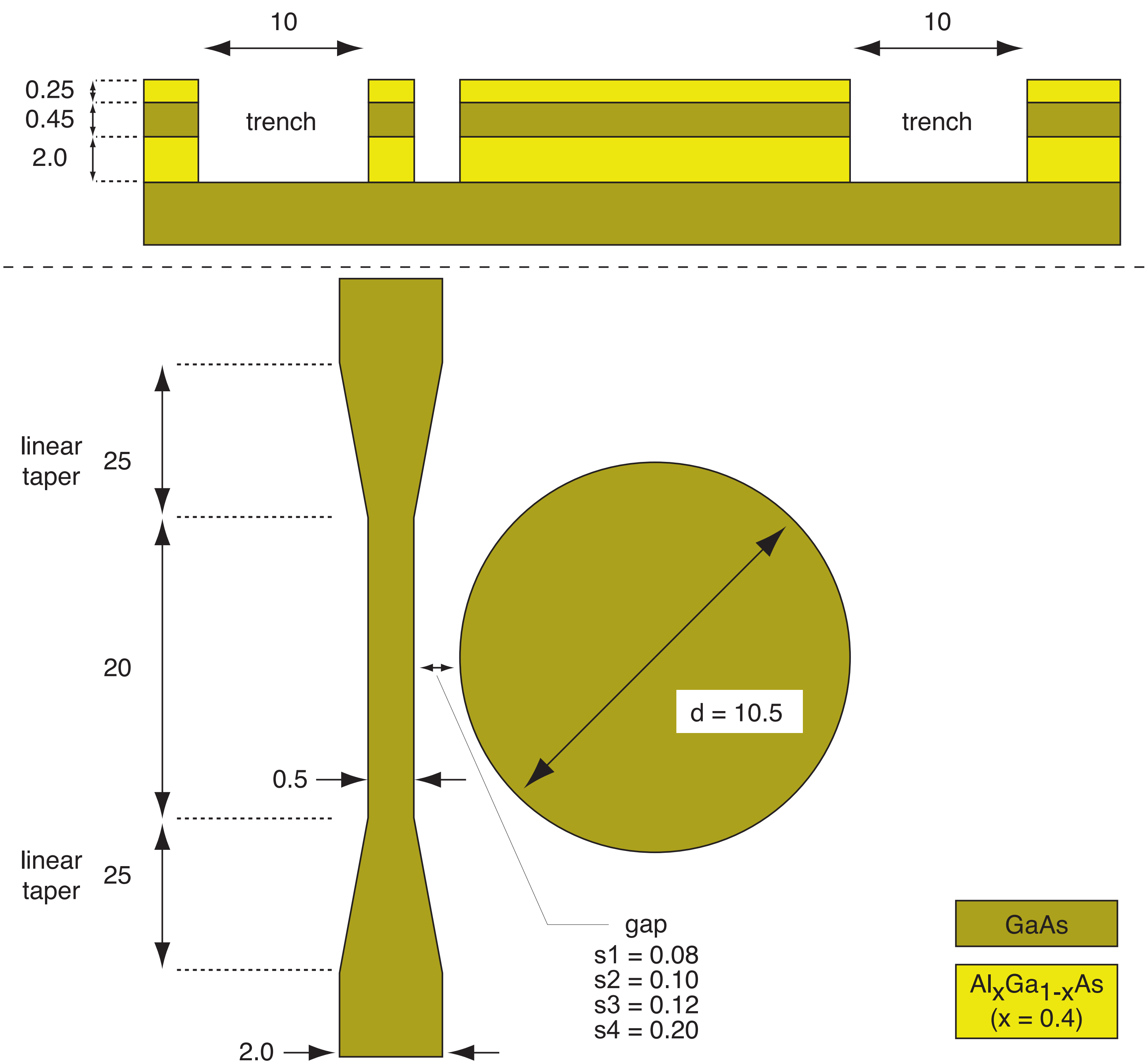


Slow Light and SCISSOR Structures



Microdisk Resonator Design

All dimensions in microns



J. E. Heebner and R. W. Boyd

Photonic Device Fabrication Procedure

(1) MBE growth

(2) Deposit oxide

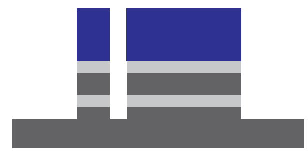
(3) Spin-coat e-beam resist

(4) Pattern inverse with e-beam & develop

(5) RIE etch oxide

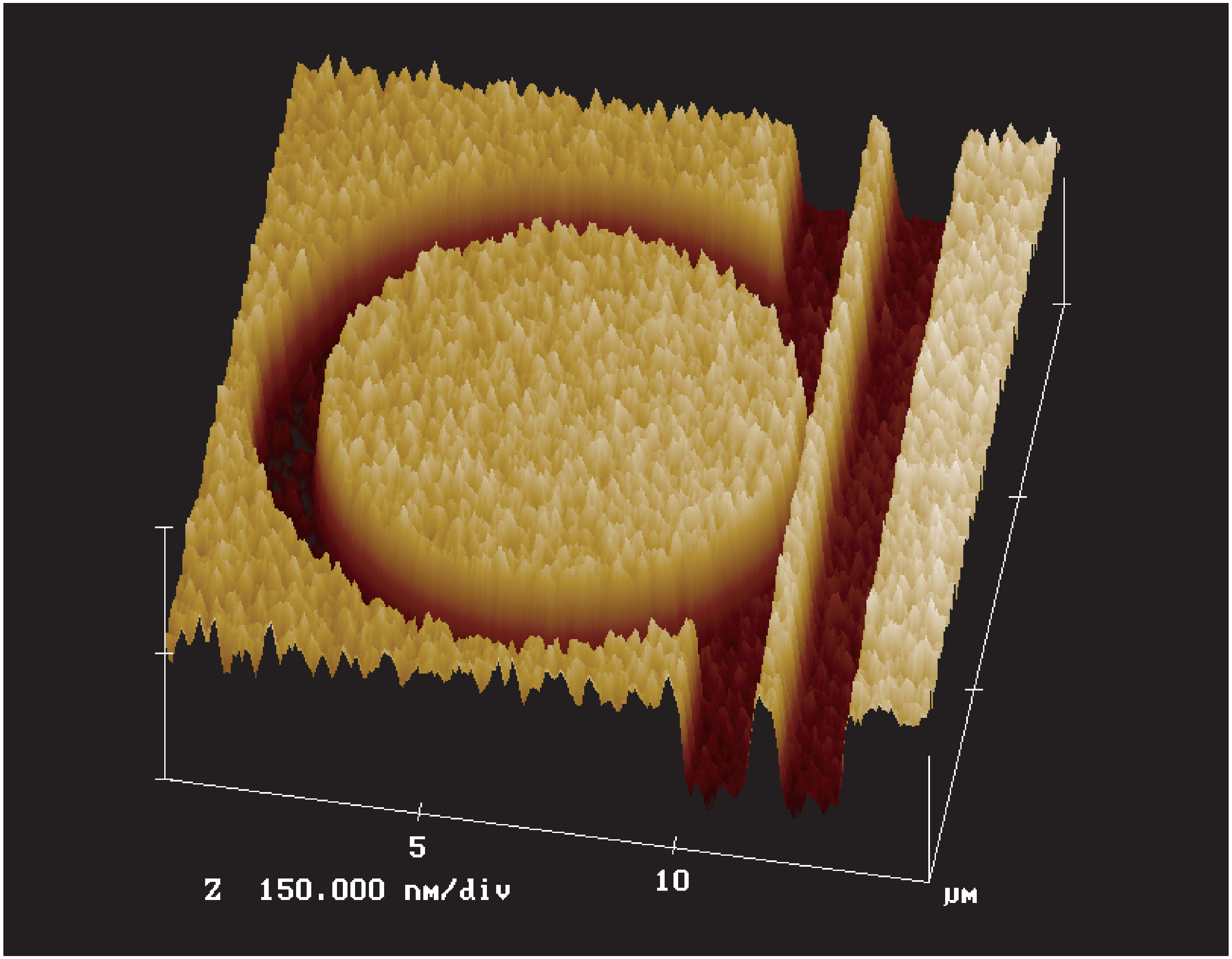
(6) Remove PMMA

(7) CAIBE etch AlGaAs-GaAs



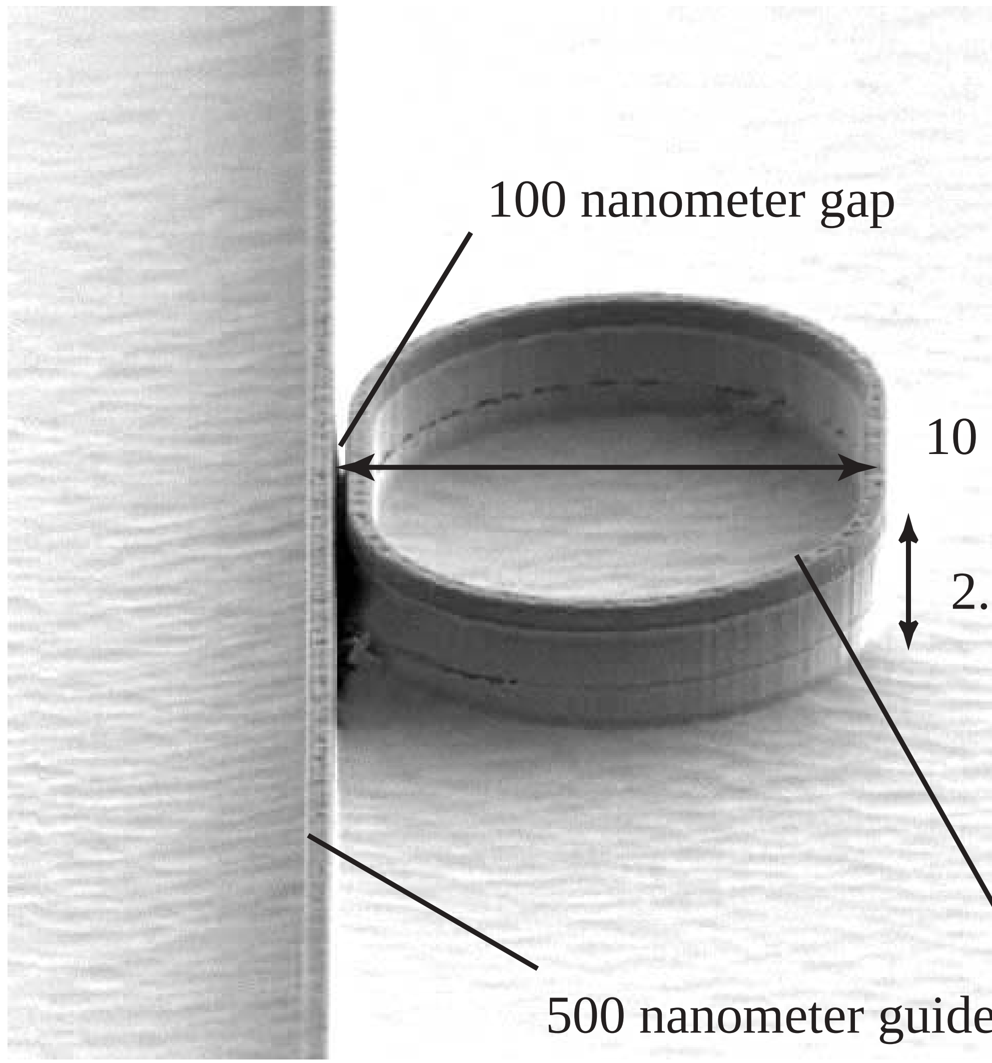
(8) Strip oxide

Disk Resonator and Optical Waveguide in PMMA Resist



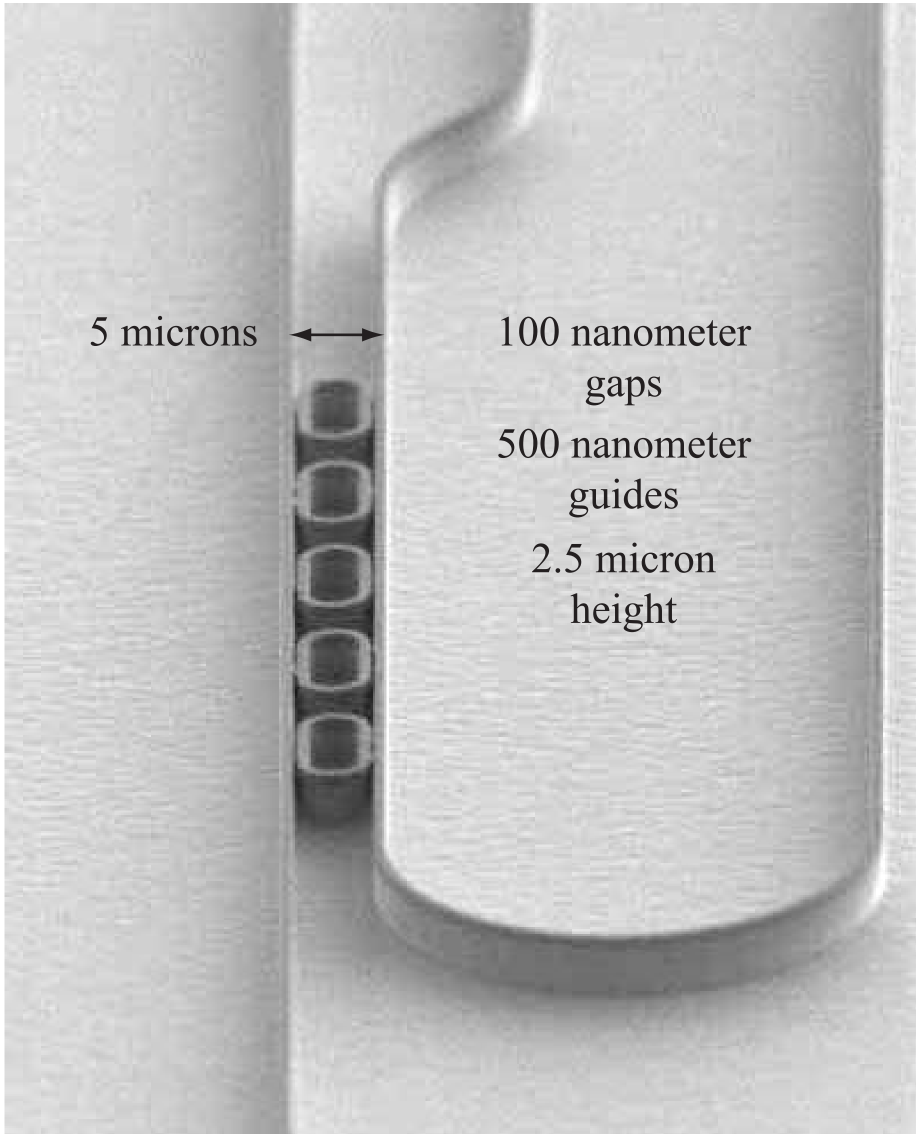
AFM

All-Pass Racetrack Microresonator

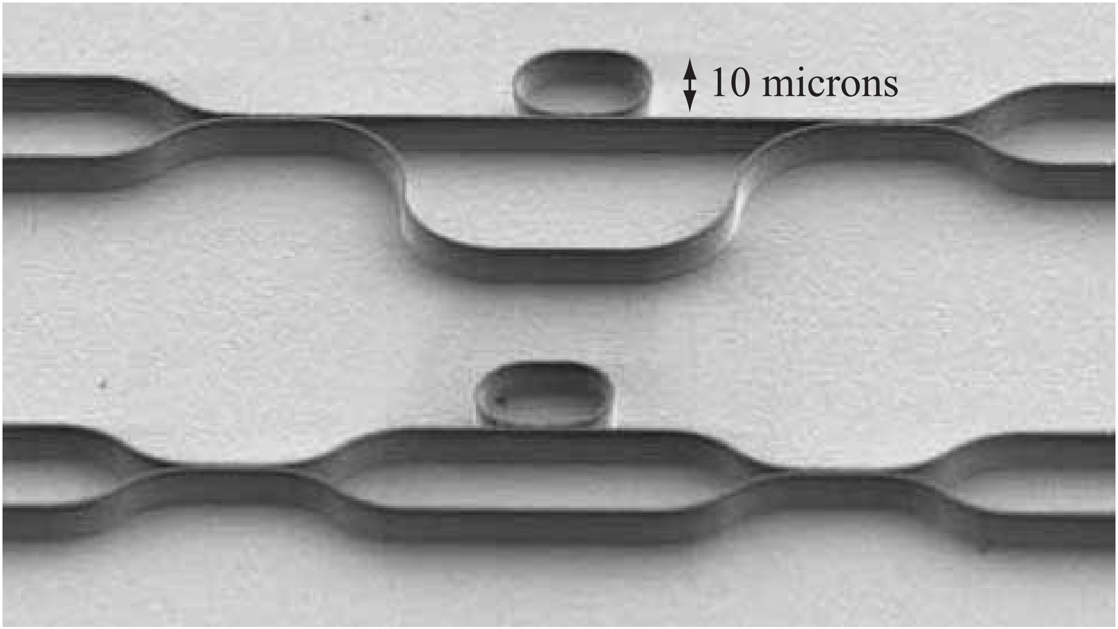


Thanks to P.T. Ho and R. Grover, U. Maryland, for help with final etch.

Five-Cell SCISSOR with Tap Channel



Resonator-Enhanced Mach-Zehnder Interferometers



~100 nanometer gaps

500 nanometer guides

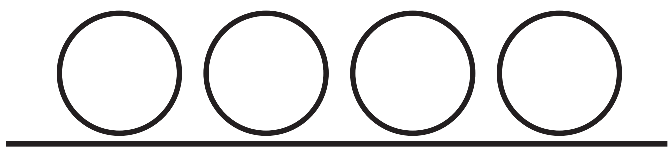
2.5 micron height

Laboratory Characterization of Photonic Structures

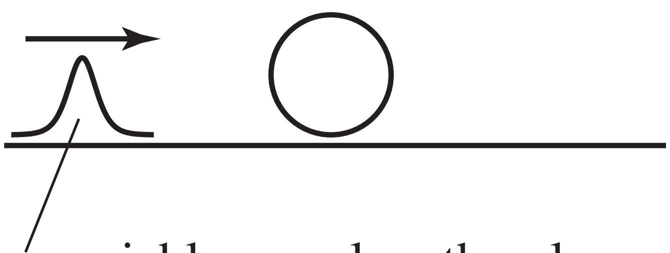
- Characterization of fiber ring-resonator devices (Proof of principle studies)
- Characterization of nanofabricated devices

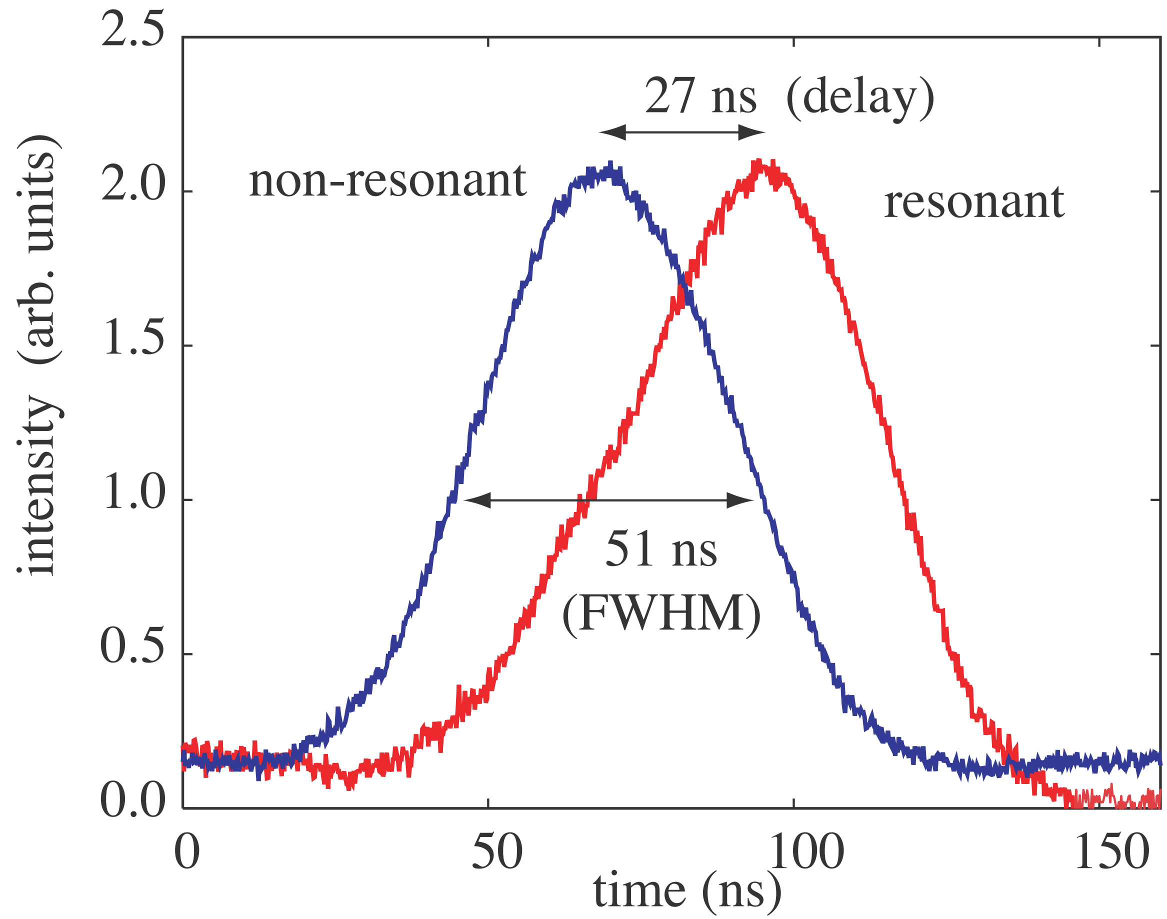
Fiber-Resonator Optical Delay Line

Fiber optical delay line:

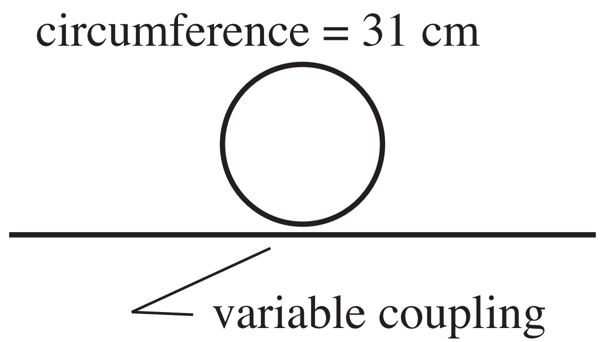


First study one element of optical delay line:





Transmission Characteristics of Fiber Ring Resonator

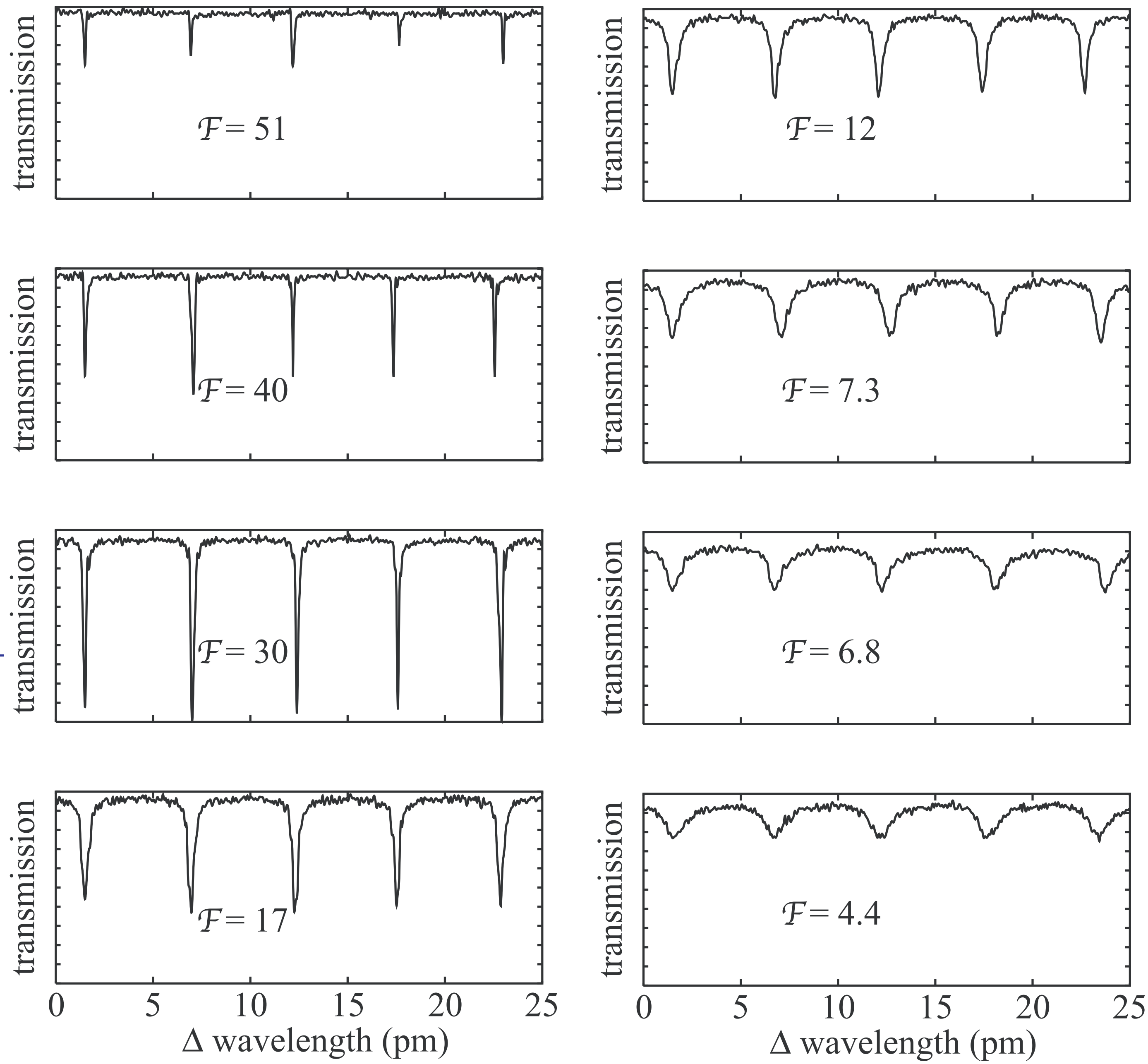


Measure transmission vs. λ for various values of the finesse

undercoupled

critically coupled

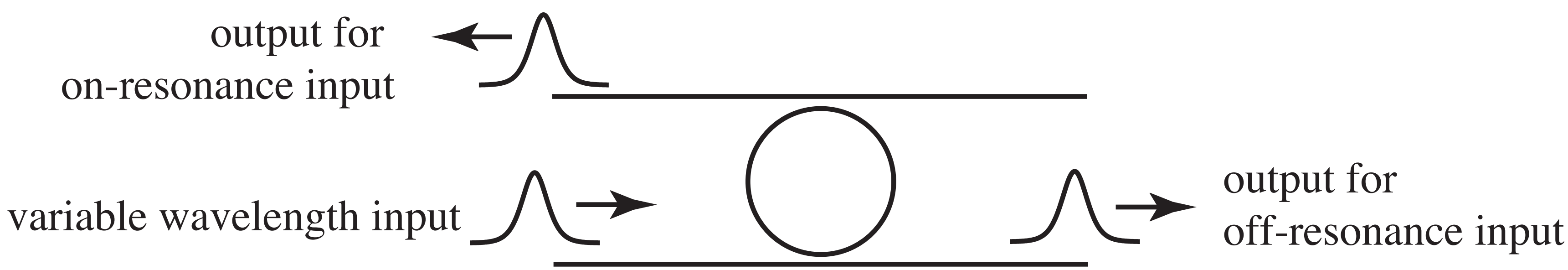
overcoupled

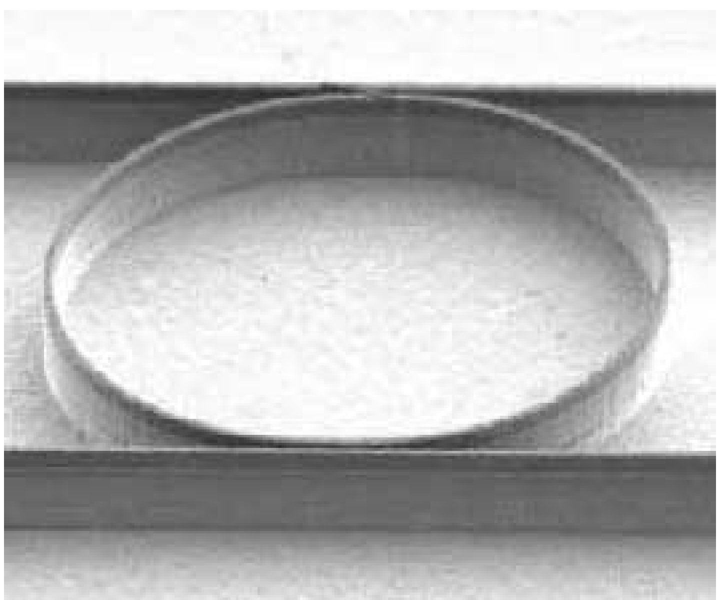


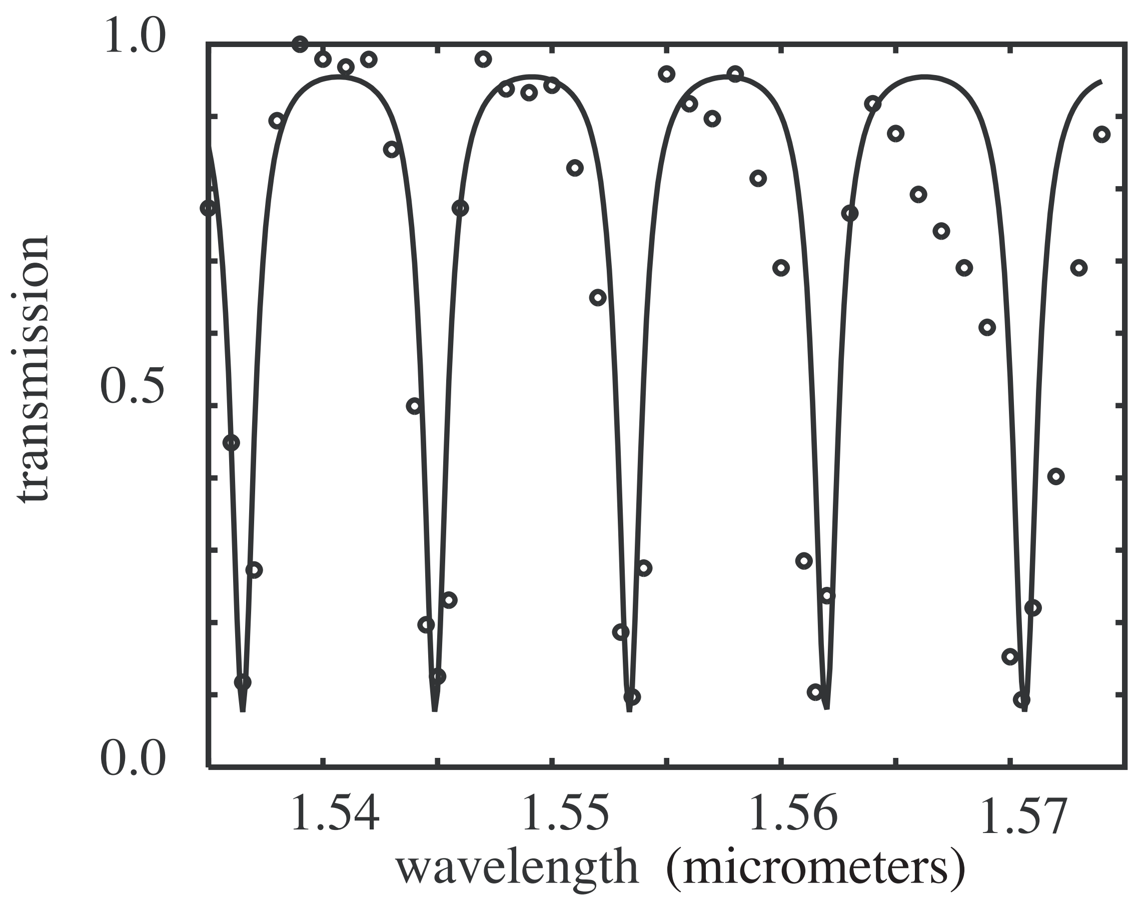
Laboratory Characterization of Photonic Structures

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

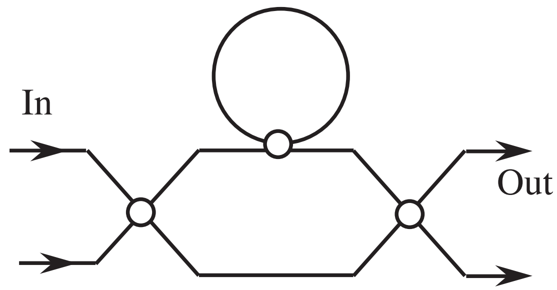
Microresonator-Based Add-Drop Filter

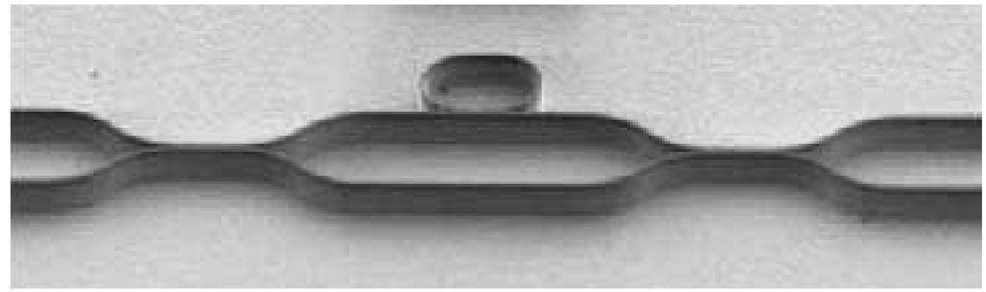




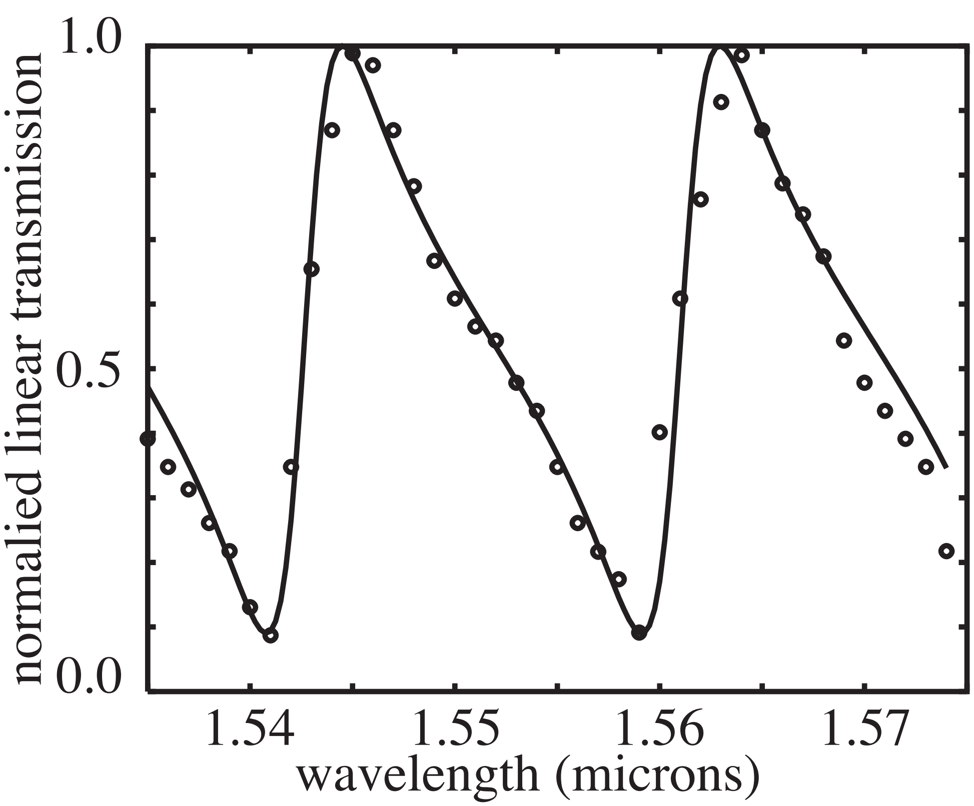


Phase Characteristics of Micro-Ring Resonator

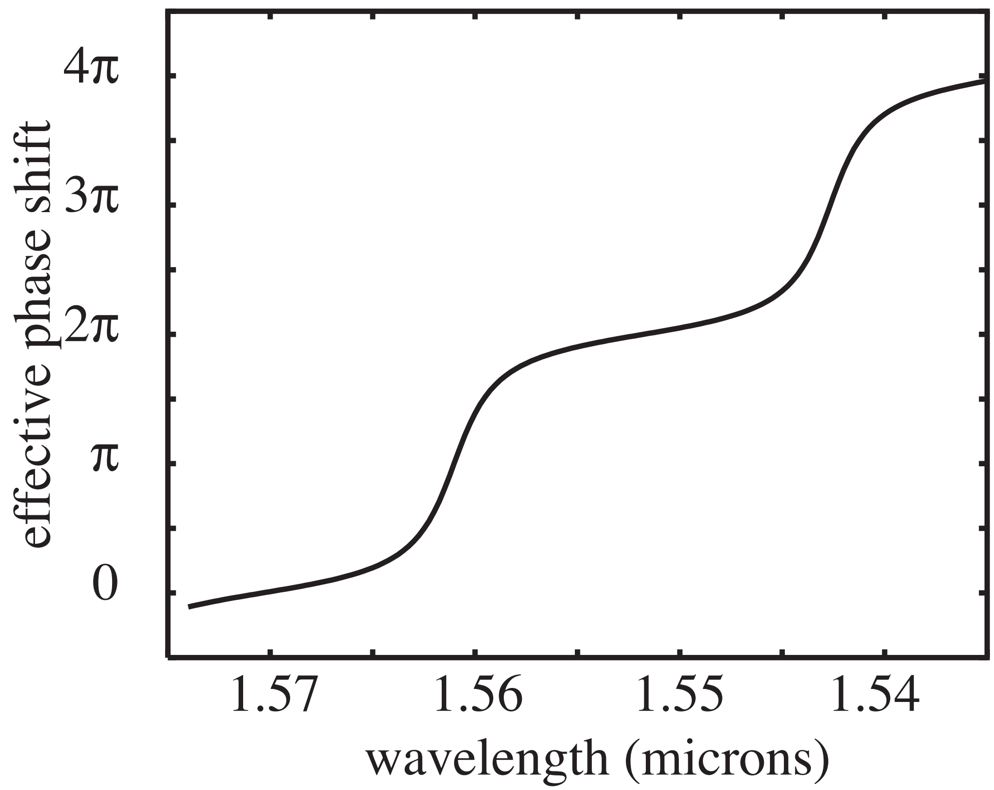




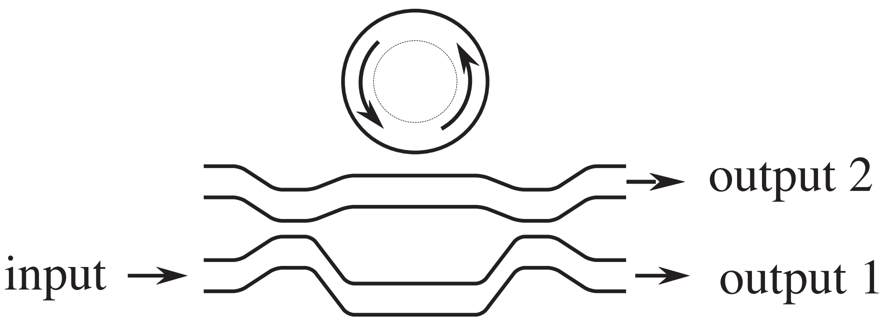
transmission

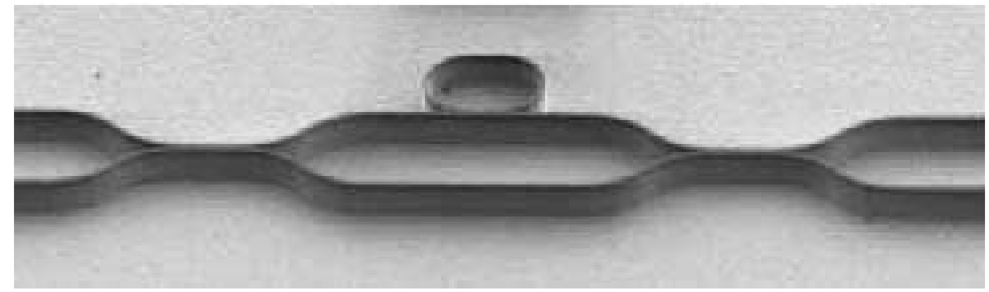


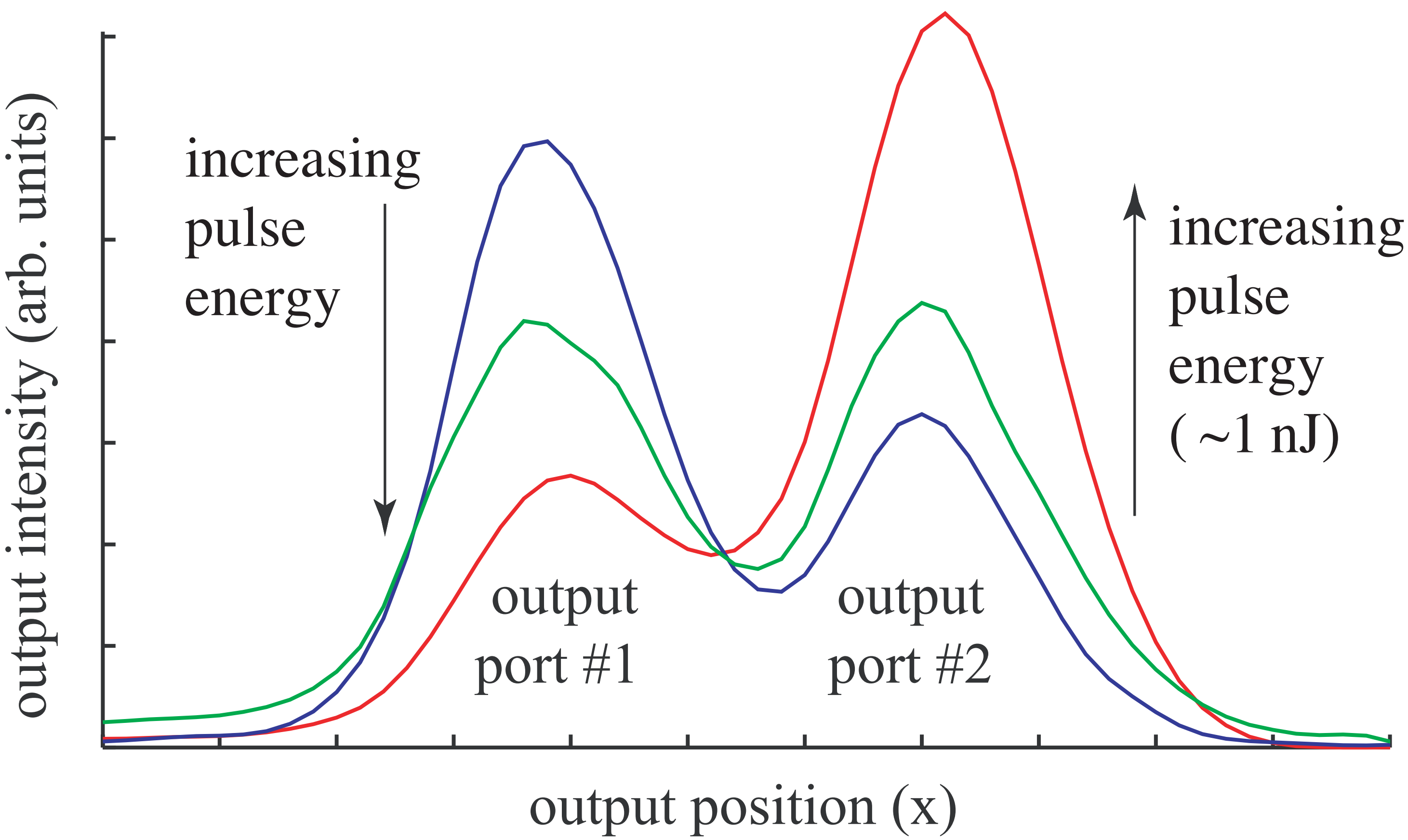
induced phase shift



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







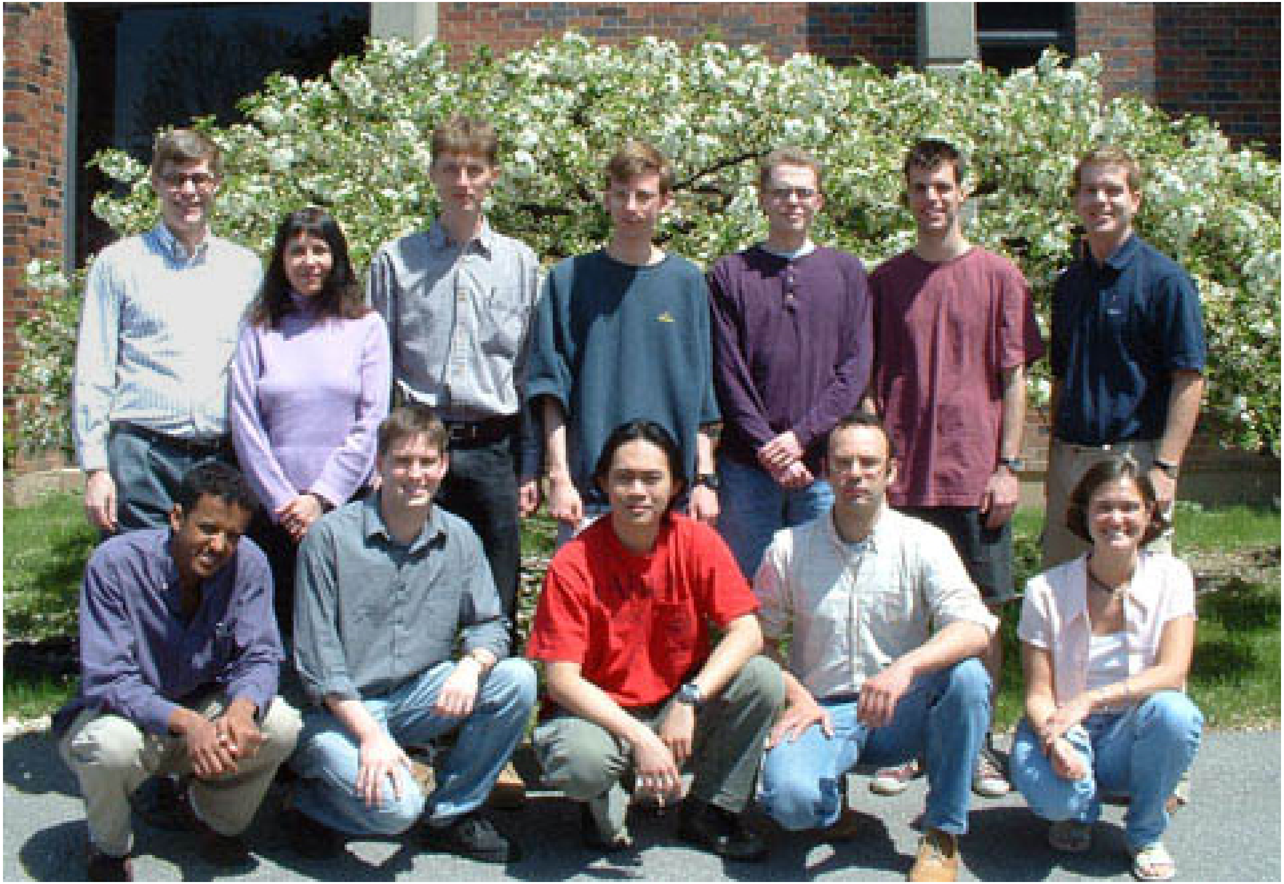
Summary

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

Argue that artificial materials hold great promise for applications in photonics because of

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

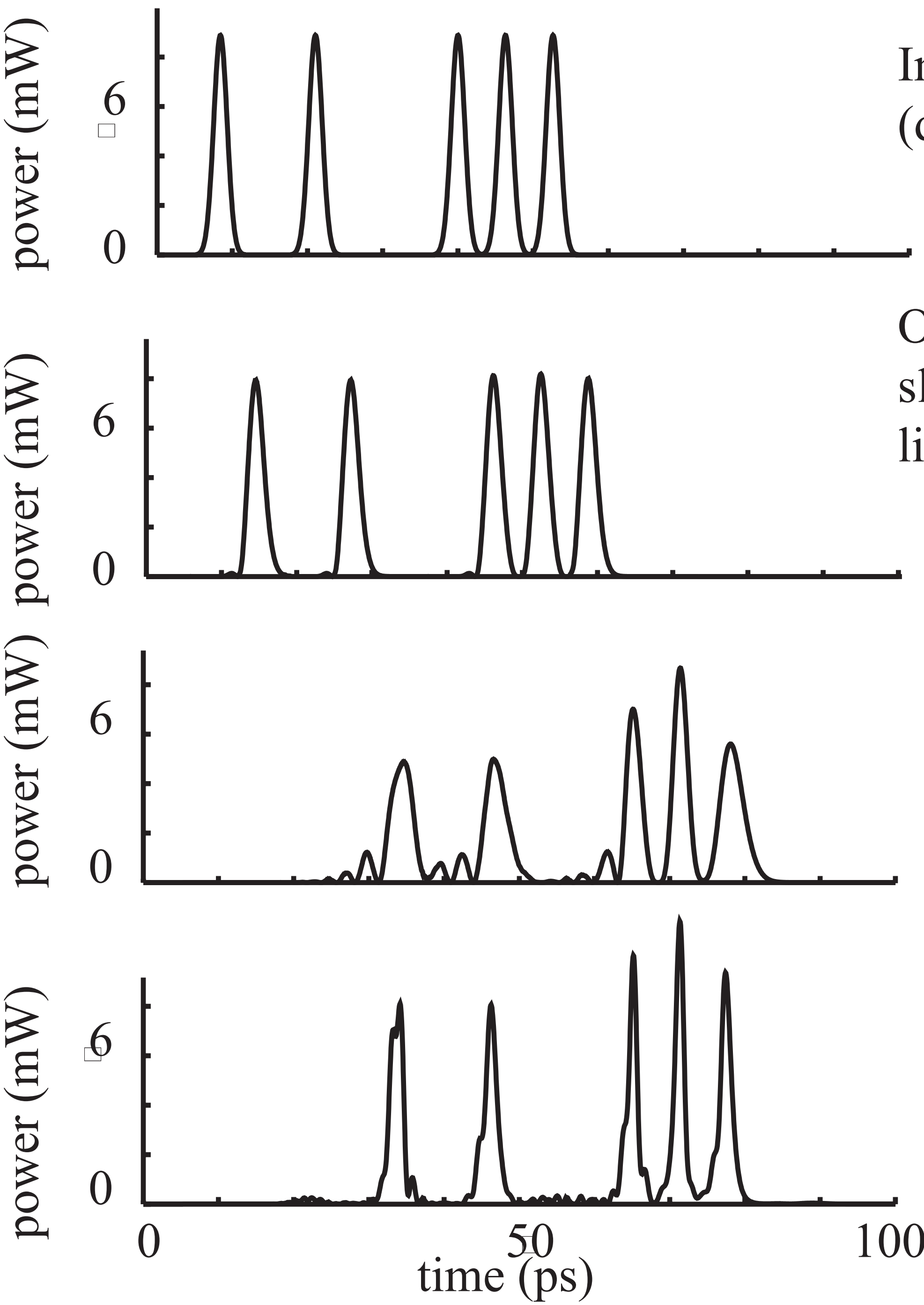
Special Thanks to my Students and Research Associates



Thank you for your attention.

Photonic Structures --What Next?

Performance of SCISSOR as Optical Delay Line



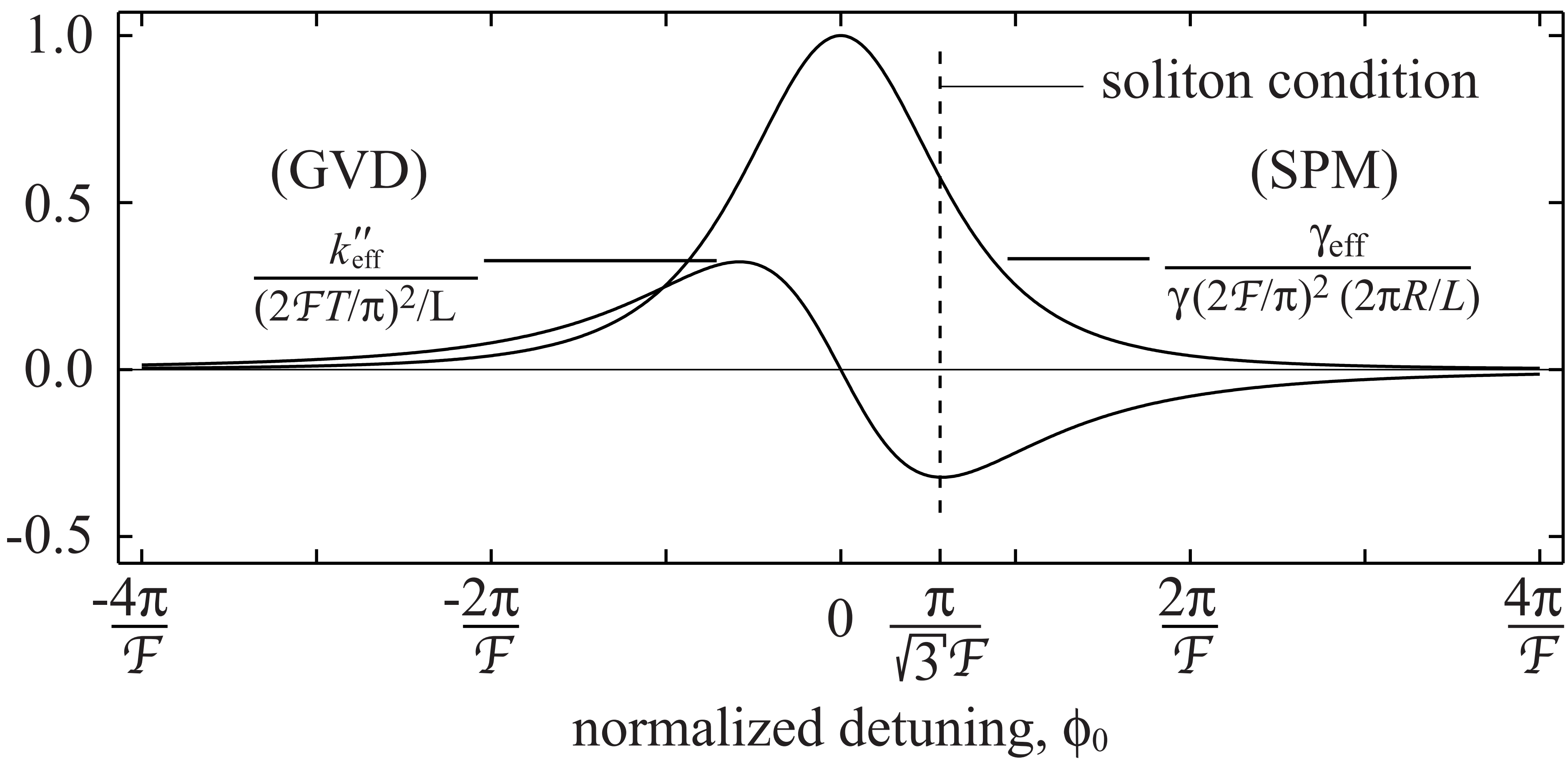
Input
(duty factor = 1/3)

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

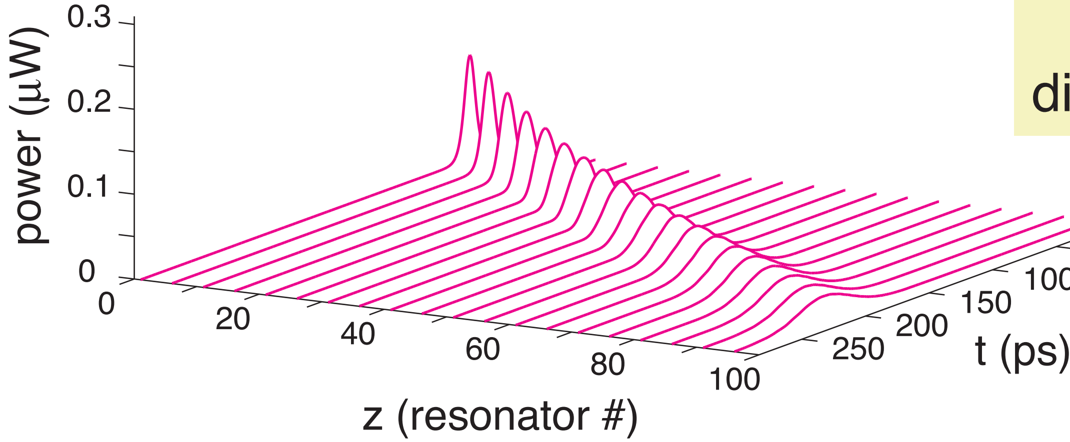
5 μm diameter resonators with a finesse of 30

SCISSOR may be constructed from 100 resonators spaced by 10 μm for a total length of 1 mm

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

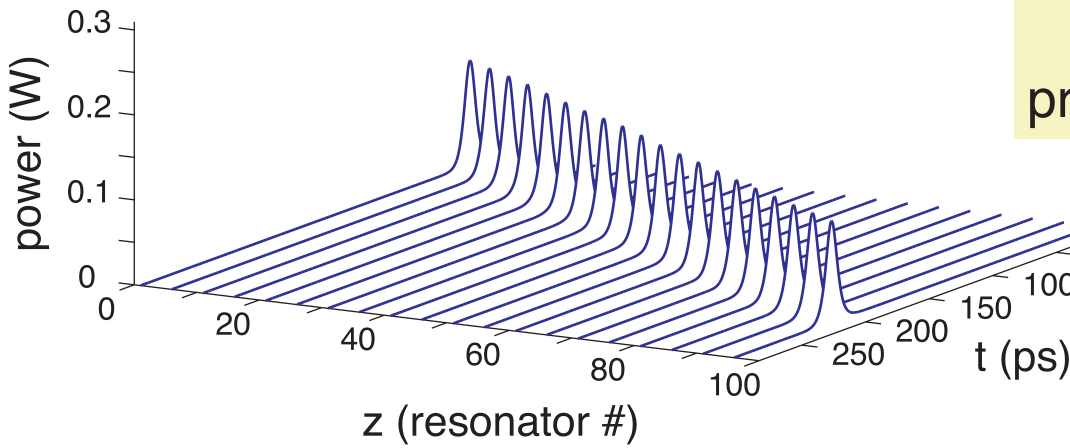
simulation assumes a chalcogenide/GaAs-like nonlinearity

Weak Pulse



pulse disperses

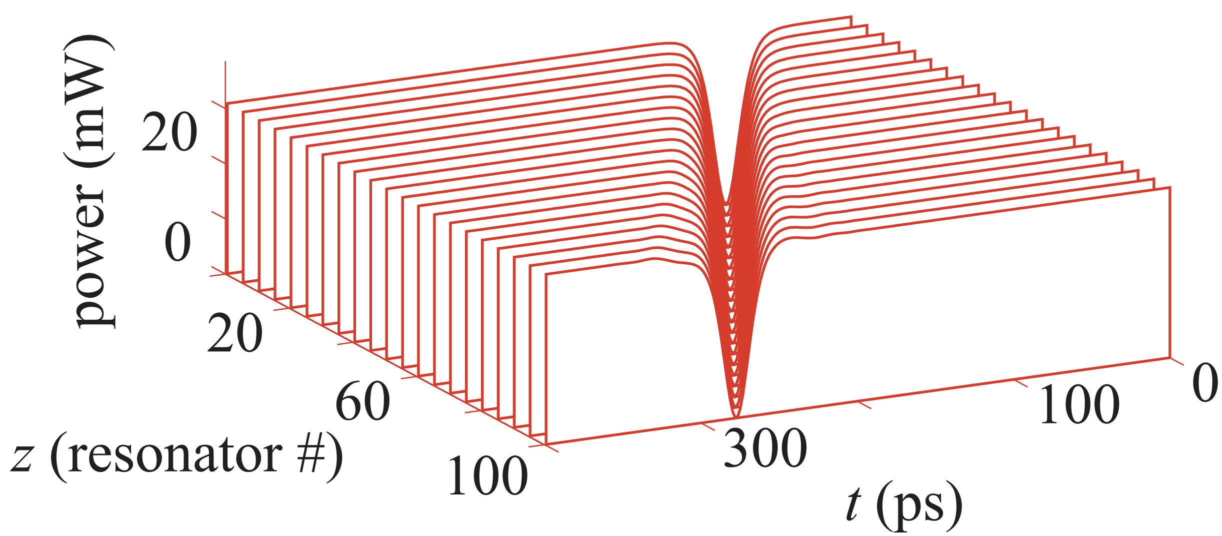
Fundamental Soliton



pulse preserved

Dark Solitons

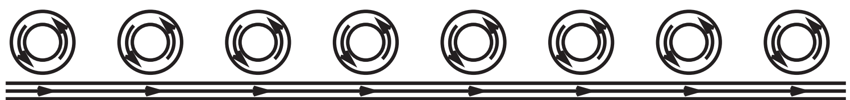
SCISSOR system also supports the propagation of dark solitons.

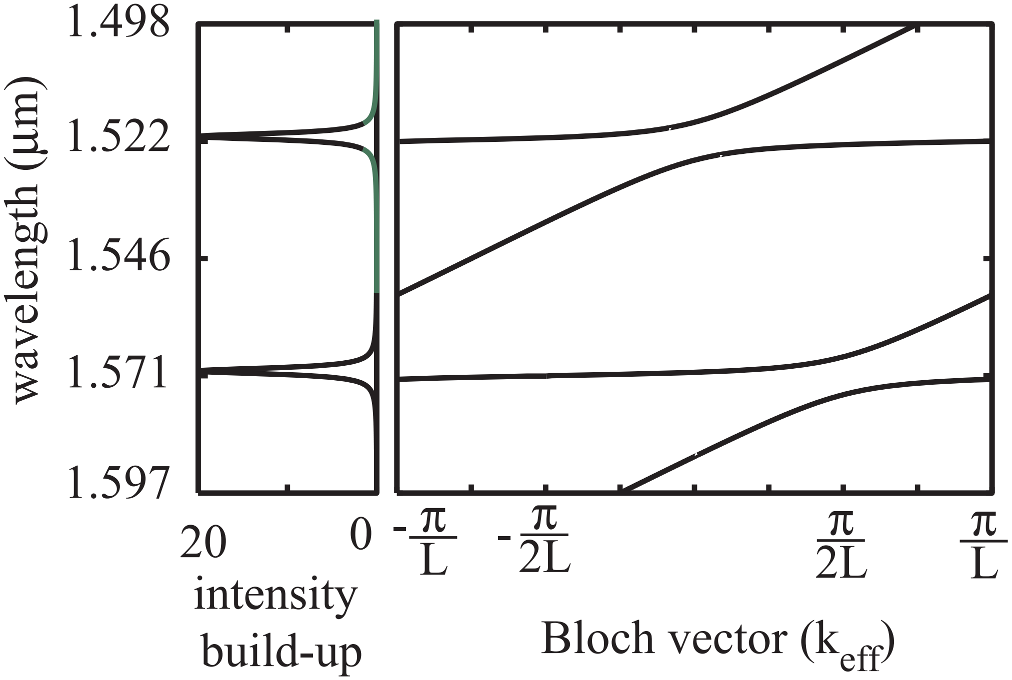


SCISSOR Dispersion Relations

Single-Guide SCISSOR

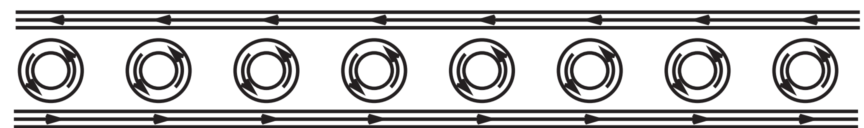
No bandgap
Large intensity buildup

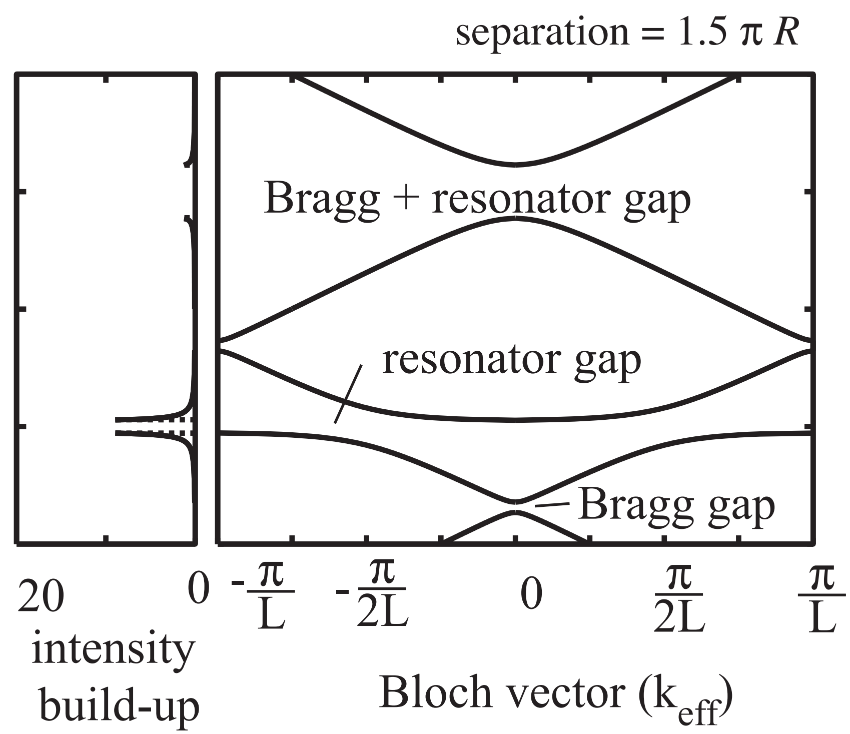




Double-Guide SCISSOR

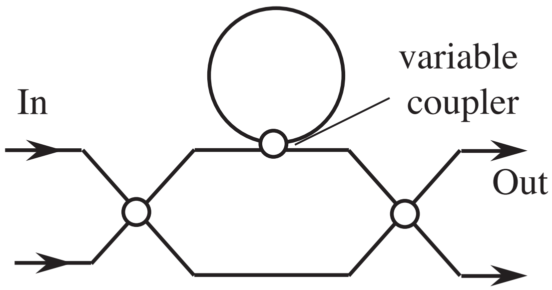
Bandgaps occur
Reduced intensity buildup

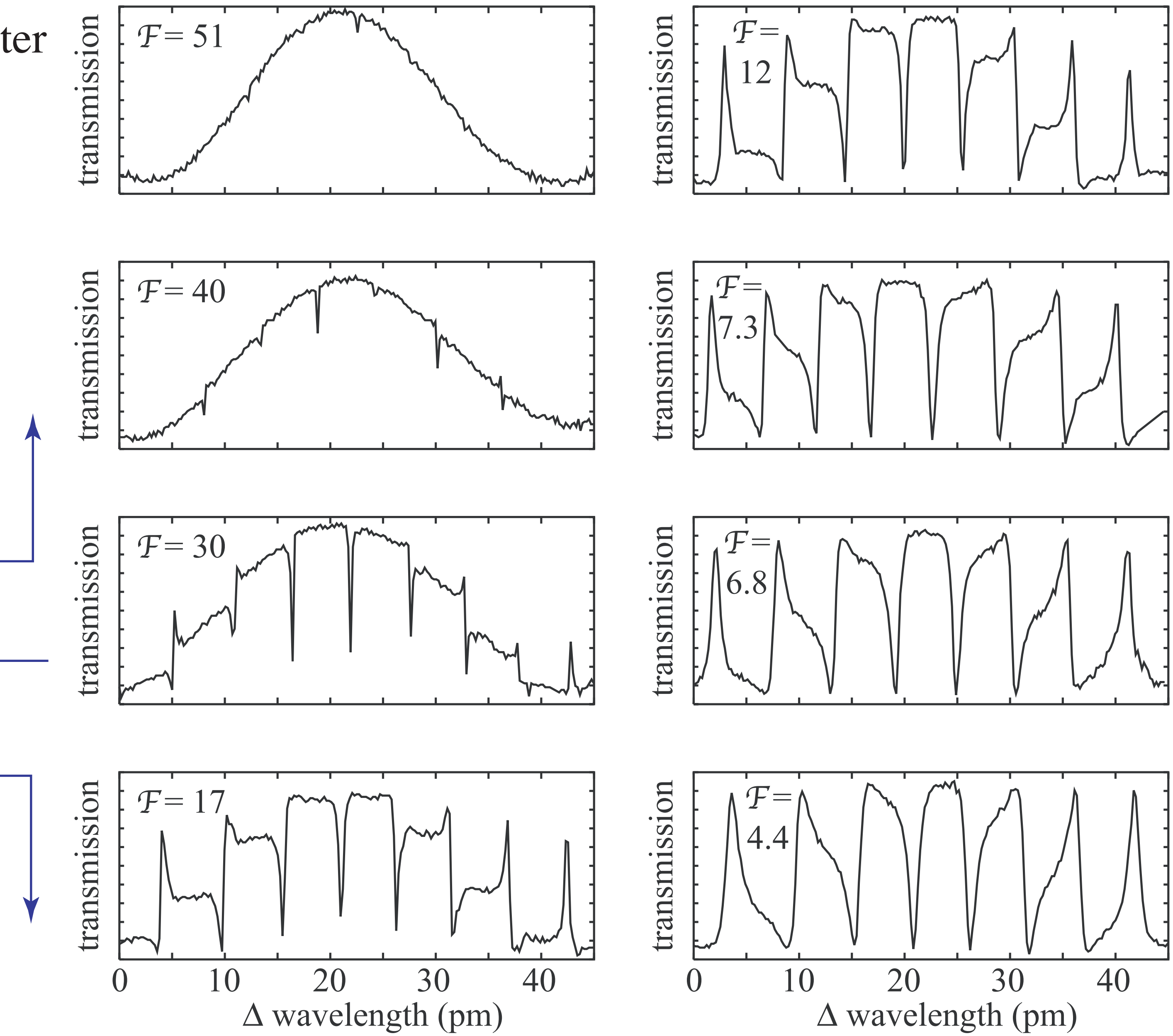




Phase Characteristics of Fiber Ring Resonator

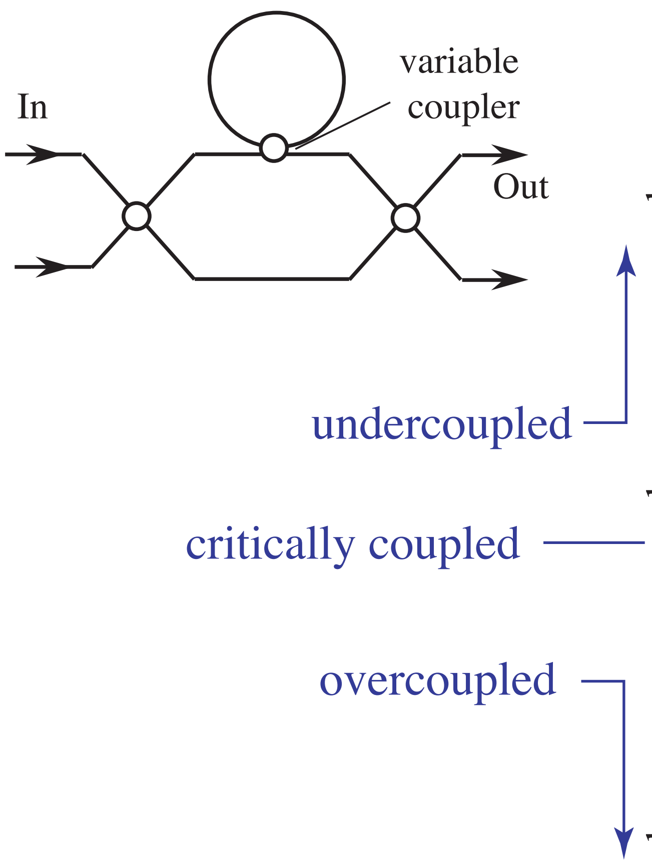
Place ring resonator inside Mach-Zhender interferometer and measure transmission versus wavelength.

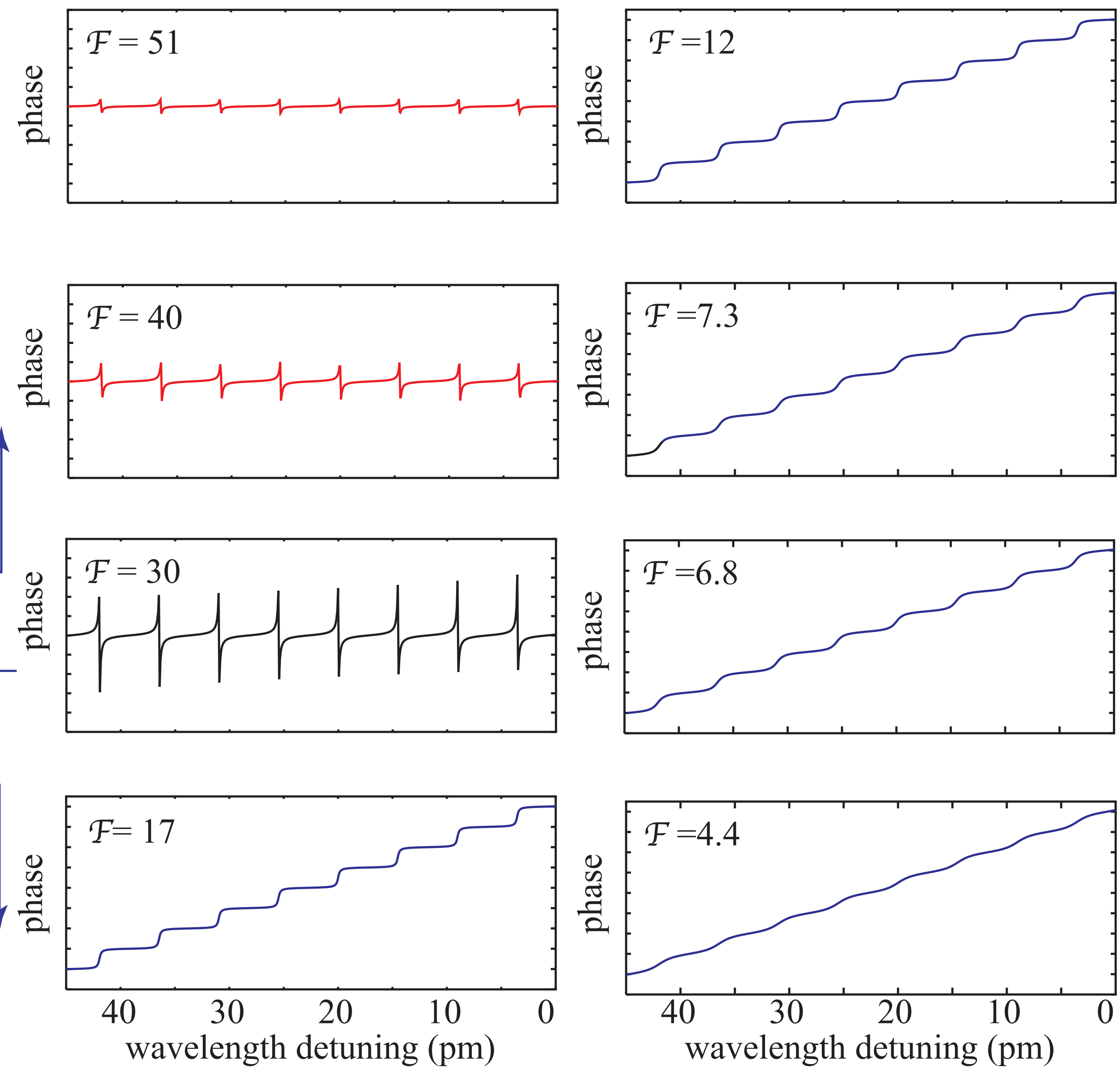




Phase Characteristics of Fiber Ring Resonator

Extracted phase strcuture





"Fast" (Superluminal) Light in SCISSOR Structures

Requires **loss** in resonator structure