"Everything Photonic"

or

Slow Light, Enhanced Optical Nonlinearities, and Photonic Biosensors based on Quantum Coherence and on Artificial Optical Materials

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Prospectus

Introduction to Slow Light and to Nonlinear Optics

Slow Light in Ruby

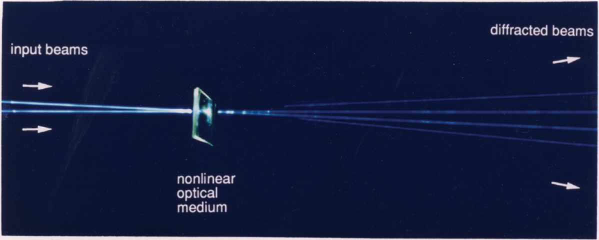
Slow Light in Artificial Materials

Slow-Light and Enhanced Optical Nonlinearities

Devices Based on Slow Light Concepts

Photonic Biosensors

Light-by-Light Scattering



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Boyd

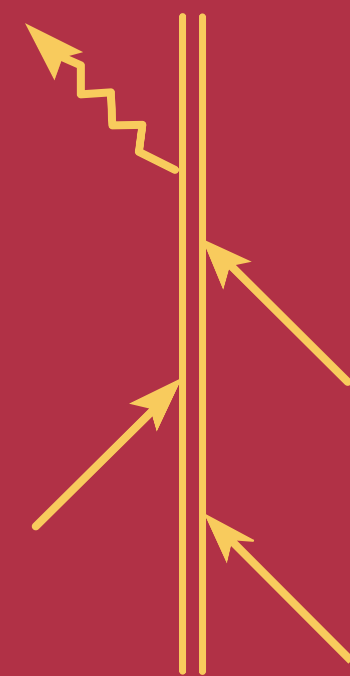
NONLINEAR OPTICS

SECOND EDITION

ACADEMIC PRESS

NONLINEAR OPTICS

SECOND EDITION



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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

E. Wolf, Progress in Optics 43

Chapter 6

"Slow" and "fast" light

by

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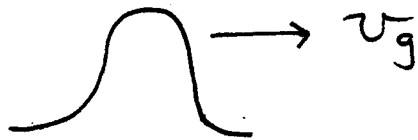
Slow Light

group velocity $\neq$ phase velocity

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!

- Want v_g very different from v_p

Need very large dispersion

Study resonances of atomic vapor

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

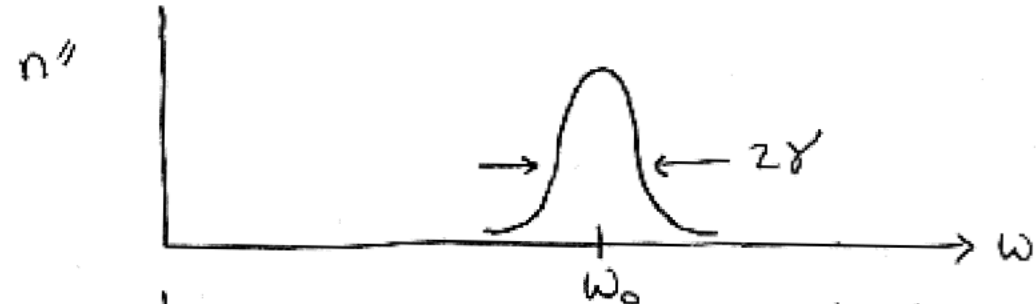
Light Propagation in Atomic Vapors

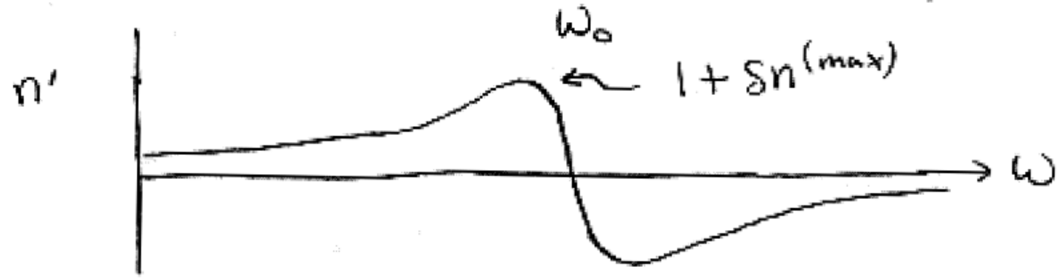
$$n = \sqrt{\varepsilon} = \sqrt{1 + 4\pi\chi} \qquad \chi = \frac{Ne^2/2m\omega_0}{(\omega_0 - \omega) - i\gamma}$$

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

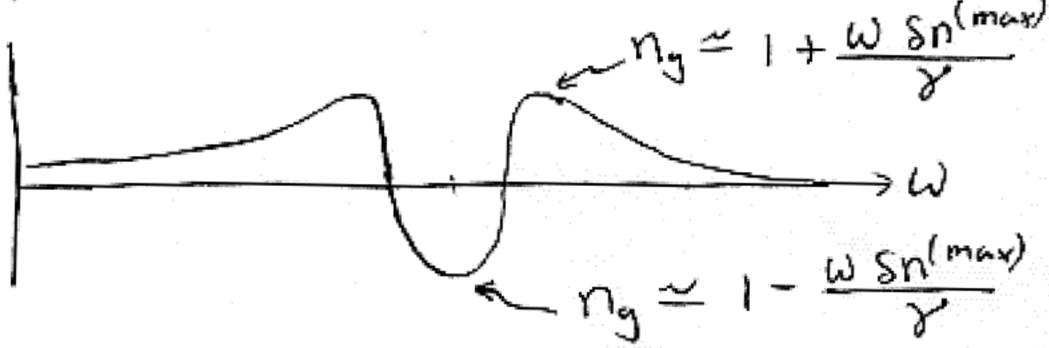
$$n' \simeq 1 + \frac{\pi N e^2}{m\omega_0} \frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 + \gamma^2}$$

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





$$n_g = n' + \omega \frac{dn'}{d\omega}$$



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

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

(But with <u>lots</u> 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)

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

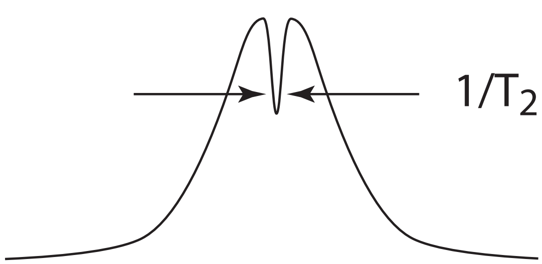
Need a large $dn/d\omega$. (How?)

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

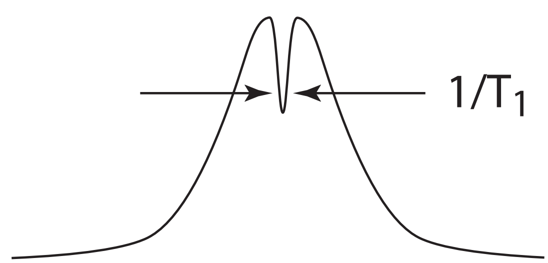
Well-known (to the few people how know it well) how to do so:

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

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



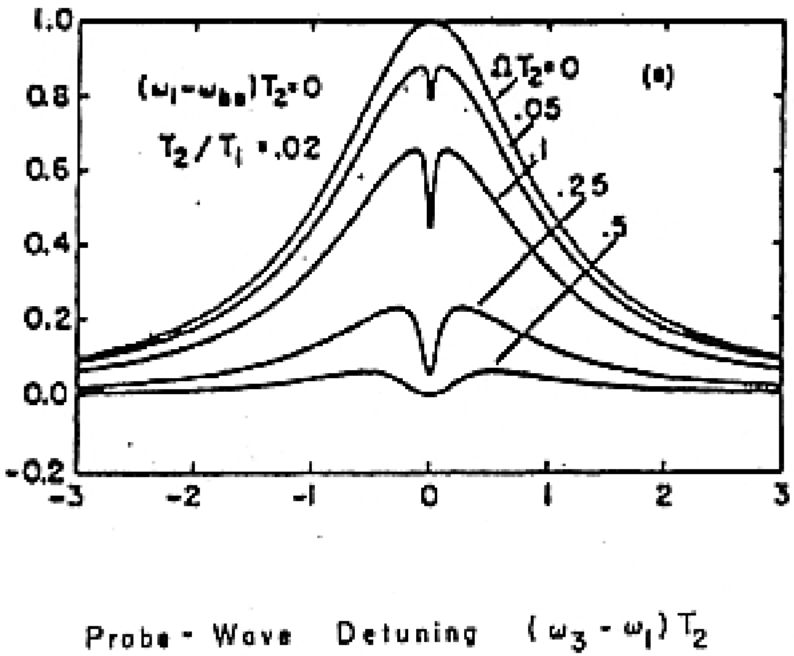
inhomogeneously broadened medium



homogeneously broadened medium (or inhomogeneously broadened)

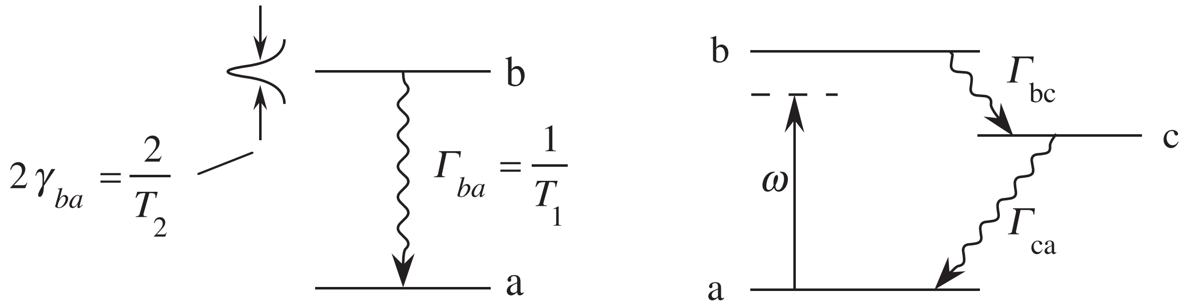
Spectral Holes in Homogeneously Broadened Materials

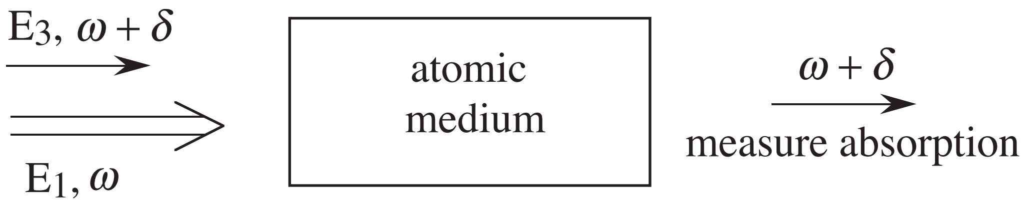
Occurs only in collisionally broadened media ($T_2 << T_1$)



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

Spectral Holes Due to Population Oscillations





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 $\delta \le 1/T_1$

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

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

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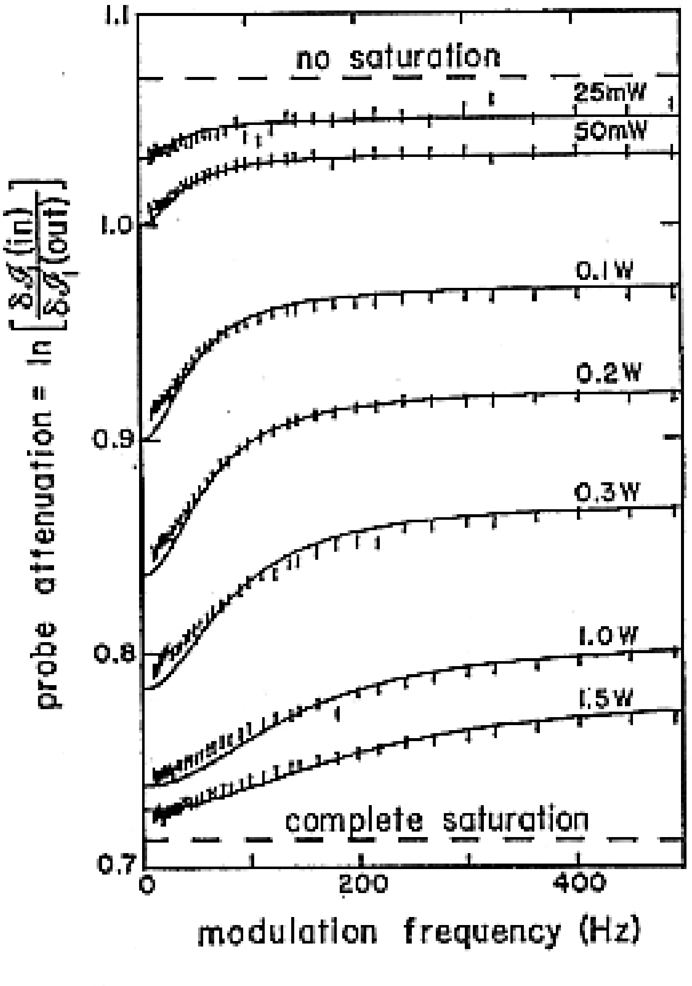
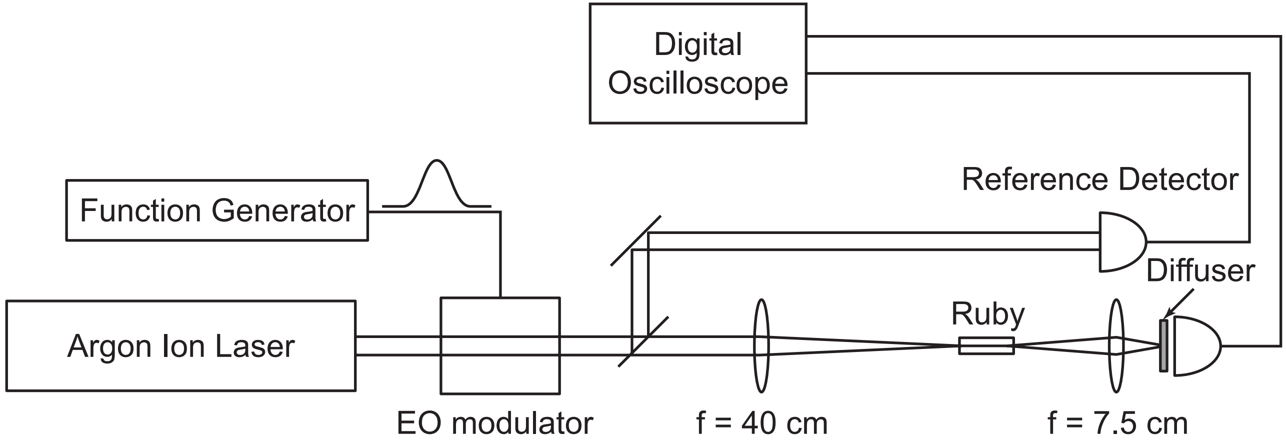


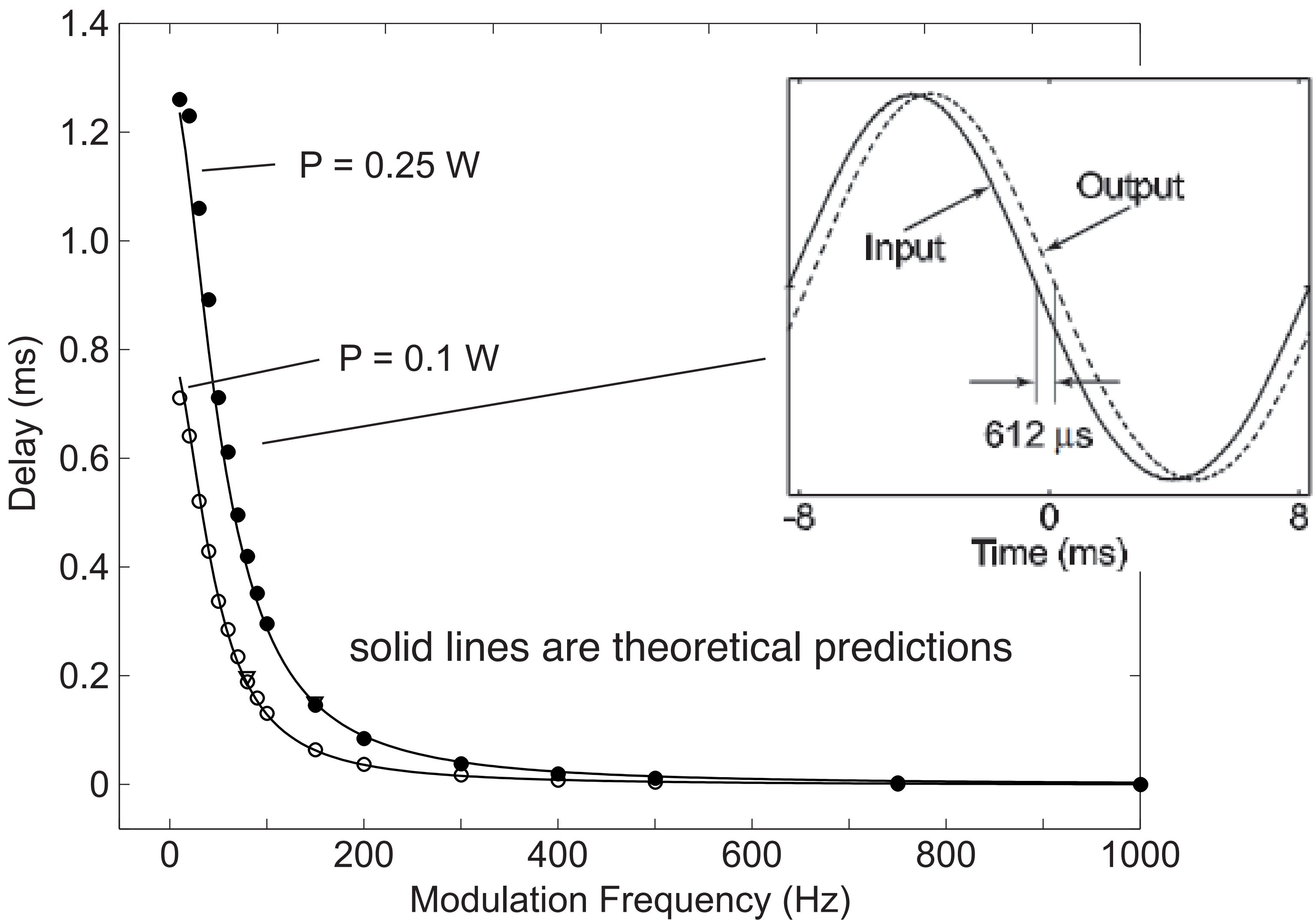
Fig. 3. Attenuation of the modulated component (probe beam) is plotted as a function of modulation frequency. The probe beam experiences decreased absorption at low modulation frequencies. The width of this hole is 37 Hz for low laser powers. The spectral hole is power broadened at high laser powers.

Experimental Setup Used to Observe Slow Light in Ruby



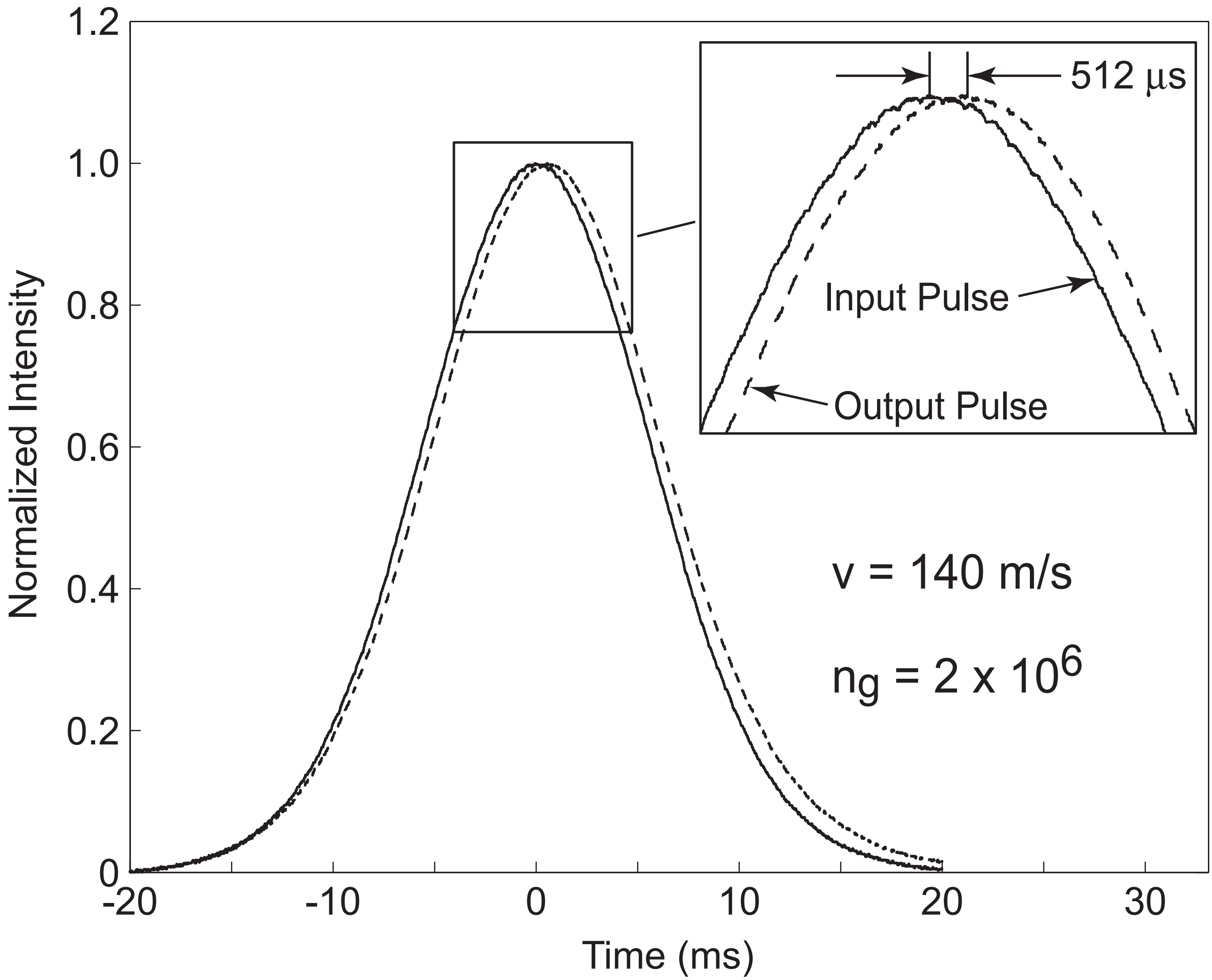
7.25 cm ruby laser rod (pink ruby)

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

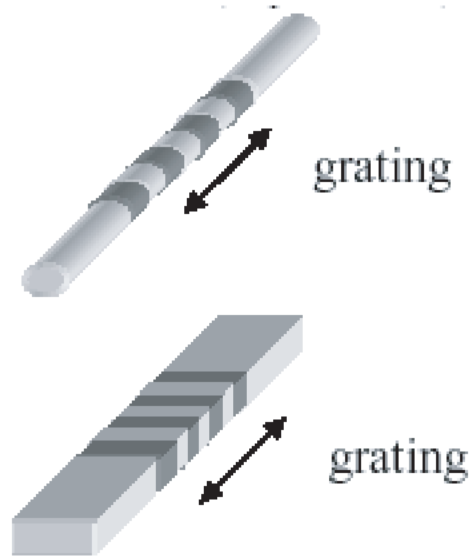


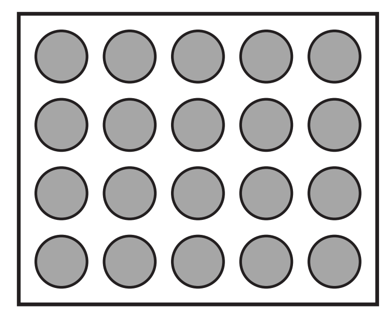
No pulse distortion!

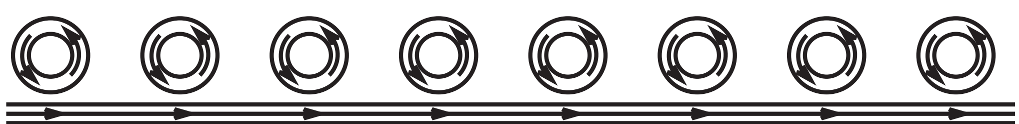
Artificial Materials for Nonlinear Optics

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



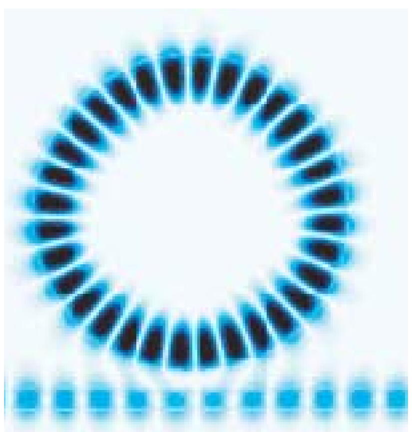




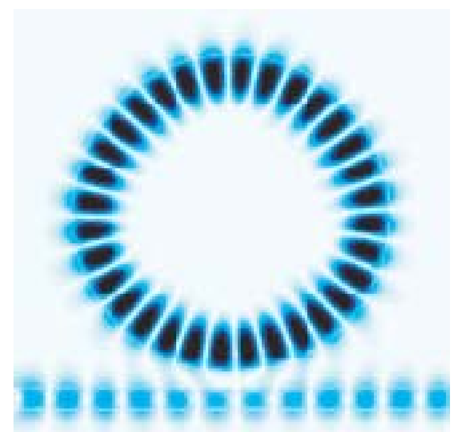
Motivation

To exploit the ability of microresonators to enhance nonlinearities and induce strong dispersive effects for creating structured waveguides with exotic properties.

A cascade of resonators side-coupled to an ordinary waveguide can exhibit:

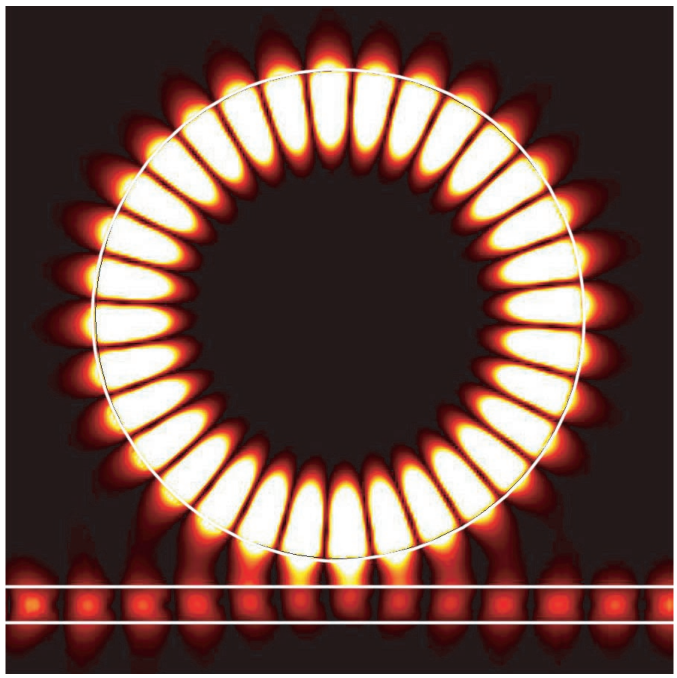


- slow light propagation
- induced dispersion
- enhanced nonlinearities

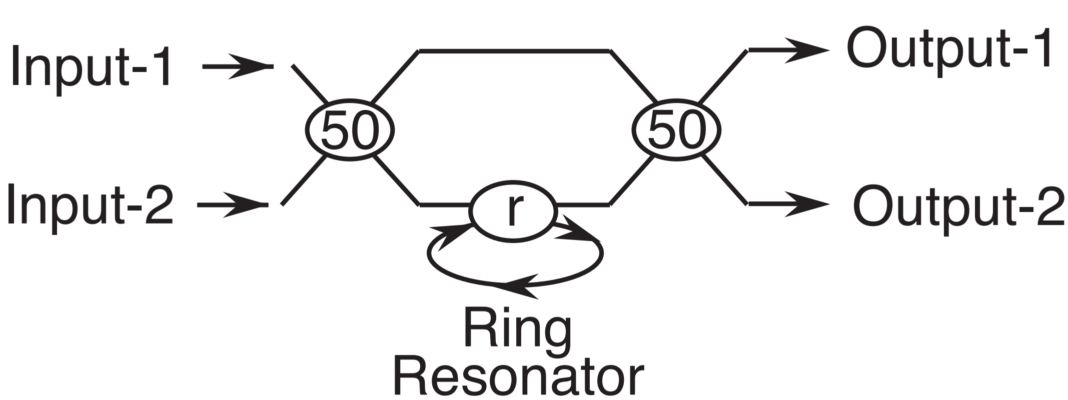


Ultrafast All-Optical Switch Based On Arsenic Triselenide Chalcogenide Glass

- We excite a whispering gallery mode of a chalcogenide glass disk.



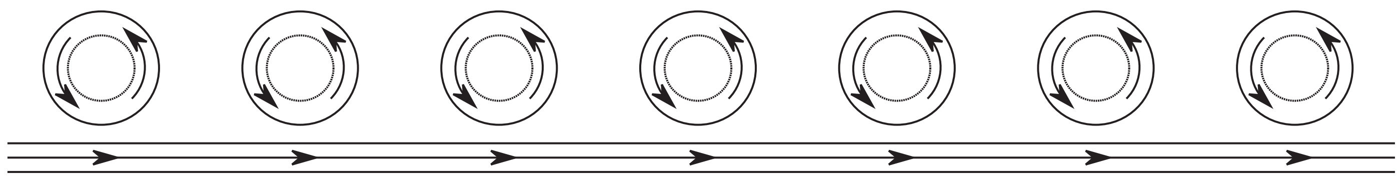
- The nonlinear phase shift scales as the square of the finesse F of the resonator. ($F \approx 10^2$ in our design)
- Goal is 1 pJ switching energy at 1 Tb/sec.



J. E. Heebner and R. W. Boyd, Opt. Lett. 24, 847, 1999.
(implementation with Dick Slusher, Lucent)

NLO of SCISSOR Devices

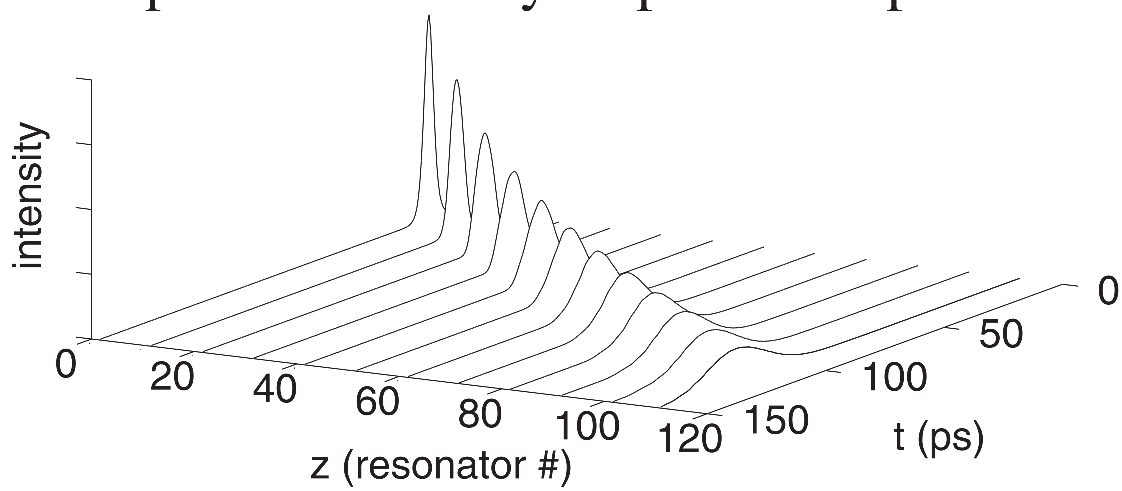
(Side-Coupled Integrated Spaced Sequence of Resonators)



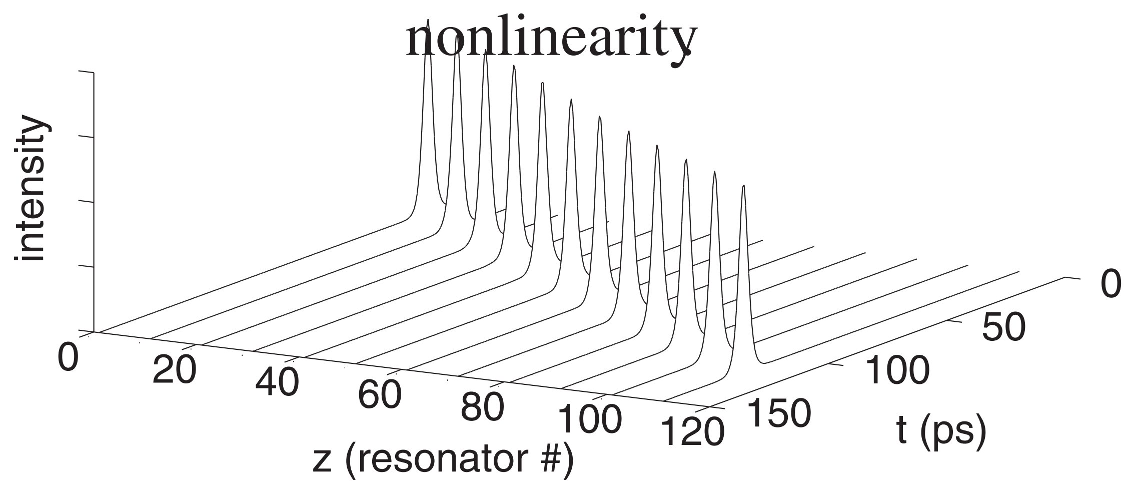
Displays slow-light, tailored dispersion, and optical solitons.

Description by NL Schrodinger eqn. in continuum limit.

- Pulses spread when only dispersion is present

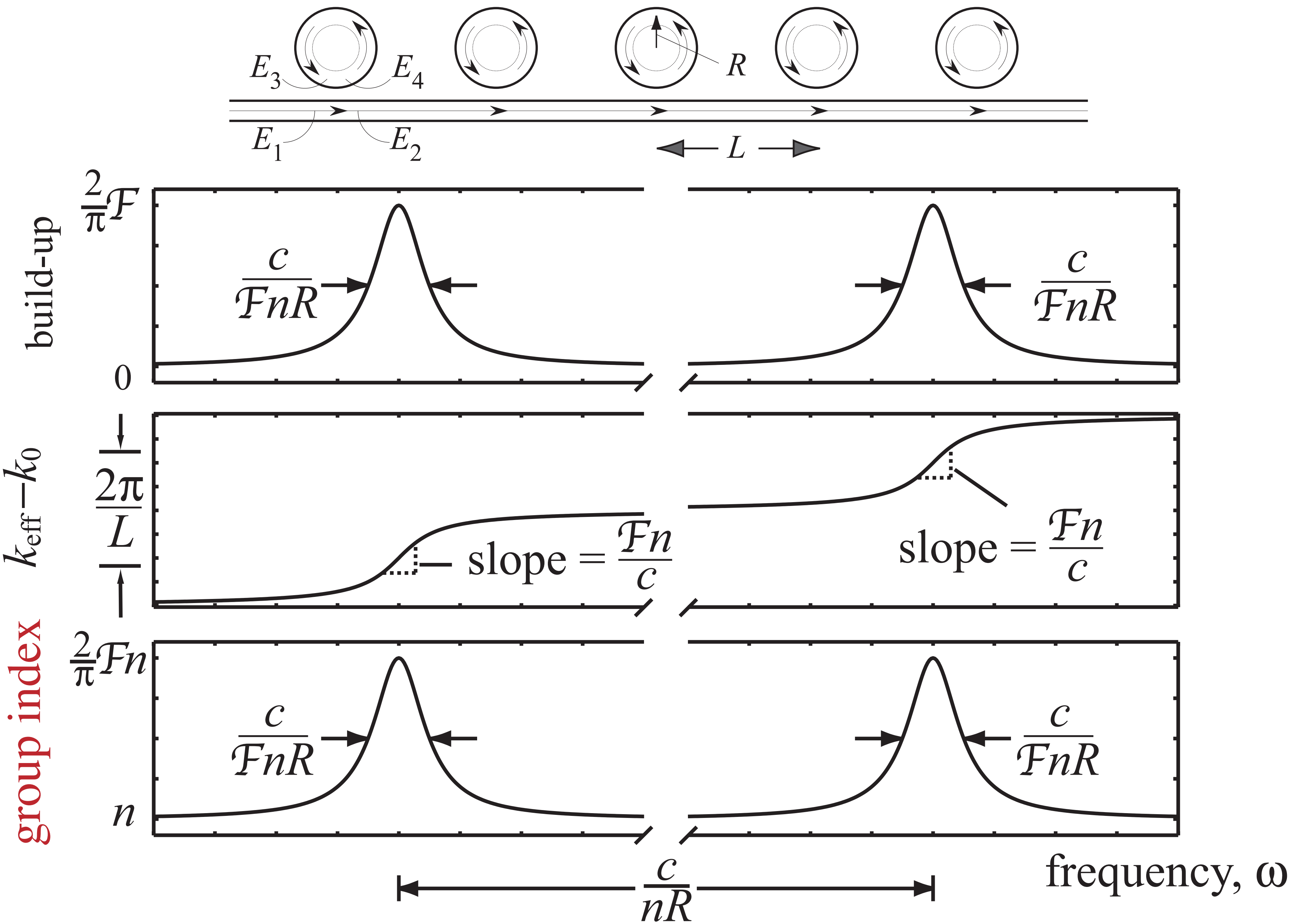


- But form solitons through balance of dispersion and nonlinearity



(J.E. Heebner, Q-Han Park and RWB)

Slow Light and SCISSOR Structures



What is the relation between slow light and enhanced optical nonlinearity?

Comment: We know that there is a connection from the work of Hau, Harris, Lukin, Soljacic, Scully, Imamoglu, Bennink and many others.

Note: For n(phase) $\approx$ 1, there is no enhancement of the electric field within the material. Thus the enhancement must be of $\chi^{(3)}$, not of E.

Possible explanation: In a slow light situation, the light spends more time interacting with the medium. Can this be the explanation for enhanced nonlinearity? (Ans: Yes and no.)

If this were the whole story, we would expect $\chi^{(3)}$, to scale in proportion to the group index n(group), which it does in some but not all situations.

What is the relation between slow light and enhanced optical nonlinearity?

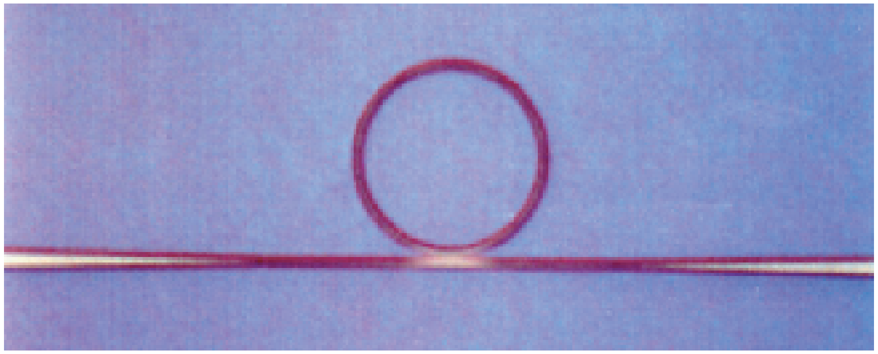
The scaling laws seem to be very different for EIT media than for structured artificial materials (PBG, CROWs, SCISSORSs, etc), because in the latter case the E field is enhanced.

To first approximation:

For EIT: $\chi^{(3)}$ scales as n(group)
For artificial materials: $\chi^{(3)}$ scales as the square of n(group)

Detailed analyses of the relation between slow light and enhanced optical nonlinearity

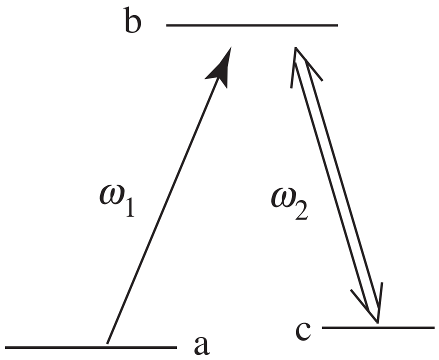
- Heebner and Boyd show that the nonlinear phase shift scales as the square of the finesse of a ring resonator. Since n(group) scales as the finesse, it follows that ϕ_{NL} scales as the square of n(group).



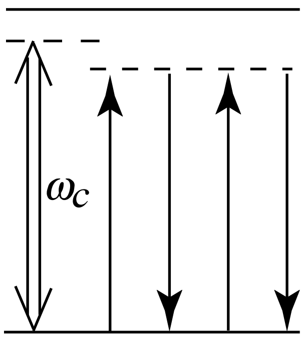
- Lukin points out that the nonlinear phase shift can be expressed as $\phi_{NL} = \delta\omega\, T$, where $T = L / (c / n_g)$ is the interaction time and where

$$\delta\omega = \mu^2 E^2 / \; (h/2\pi)^2 \Delta$$

is the Stark shift of the optical transition. This model predicts that ϕ_{NL} scales as n(group).

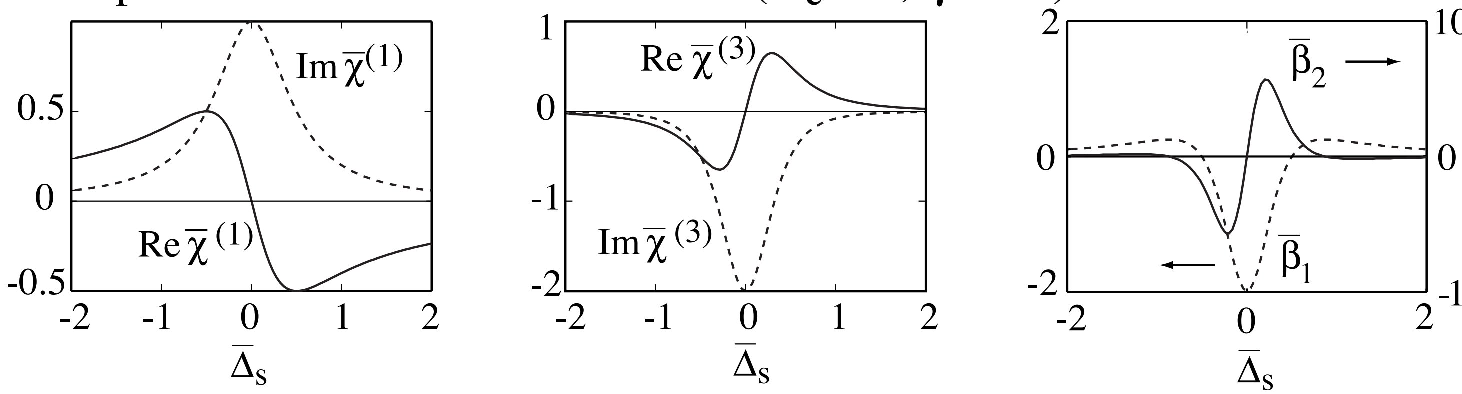


Unwanted Complication in Two-Level-Atom EIT

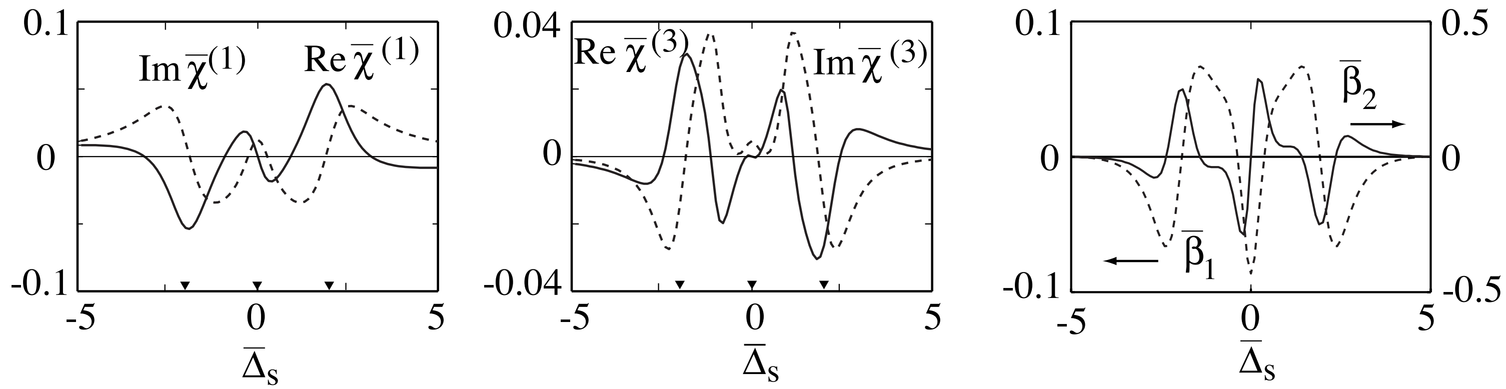


Im $\chi^{(3)}$ is proportional to n_g, but Re $\chi^{(3)}$ is not.

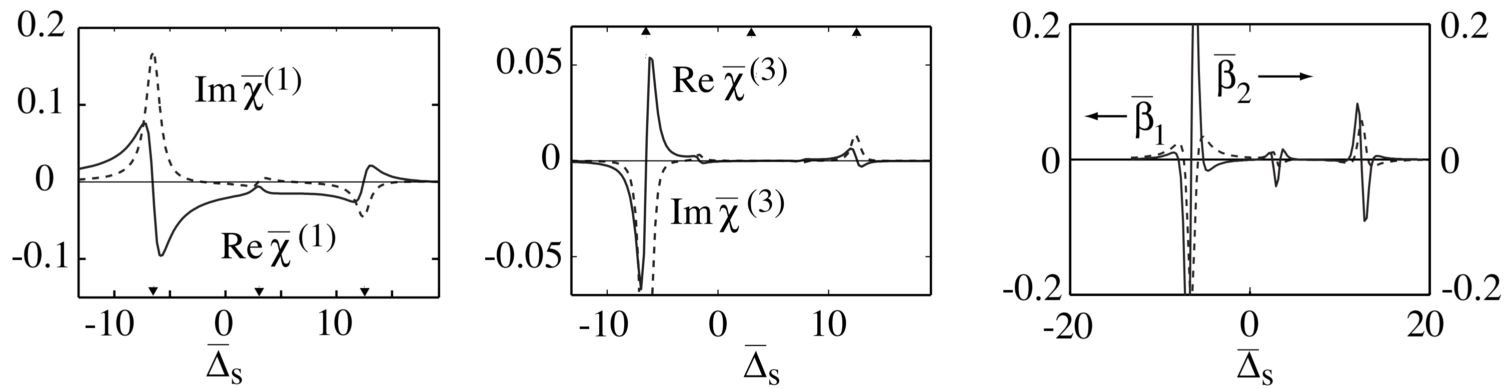
Response in absence of control field ($\Omega_c = 0$, $\gamma = 0.5$)



Response with a moderate, centrally tuned control field ($\Omega_c = 2$, $\Delta_c = 0$, $\gamma = 0.5$)



Response with a stronger, detuned control field ($\Omega_c = 9$, $\Delta_c = 3$, $\gamma = 0.5$)



Bennink et al., Phys. Rev. A, 2001.

What is the relation between slow light and enhanced optical nonlinearity?

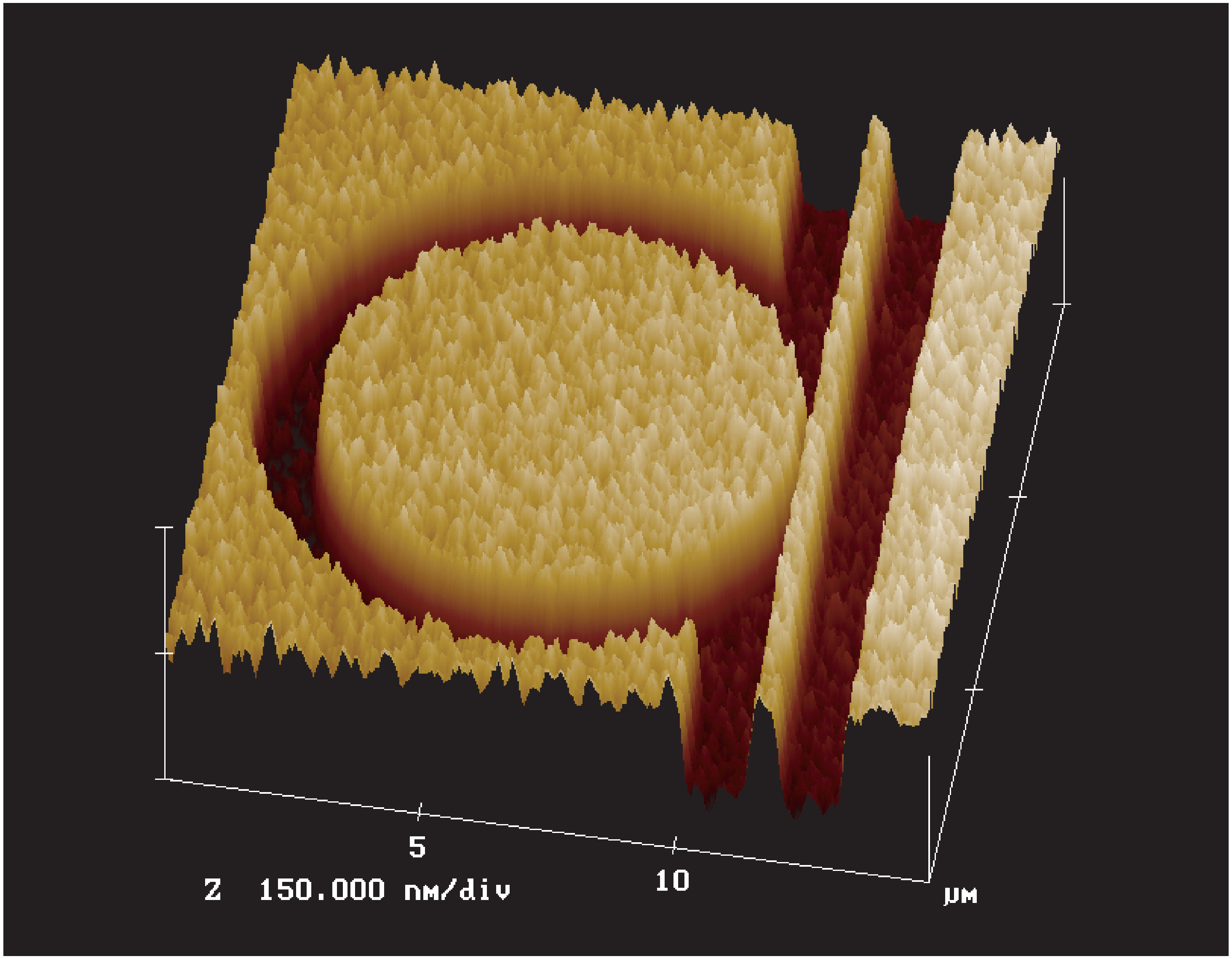
Summary: This remains a somewhat open question.

Nanofabrication

- Materials (artificial materials)
- Devices

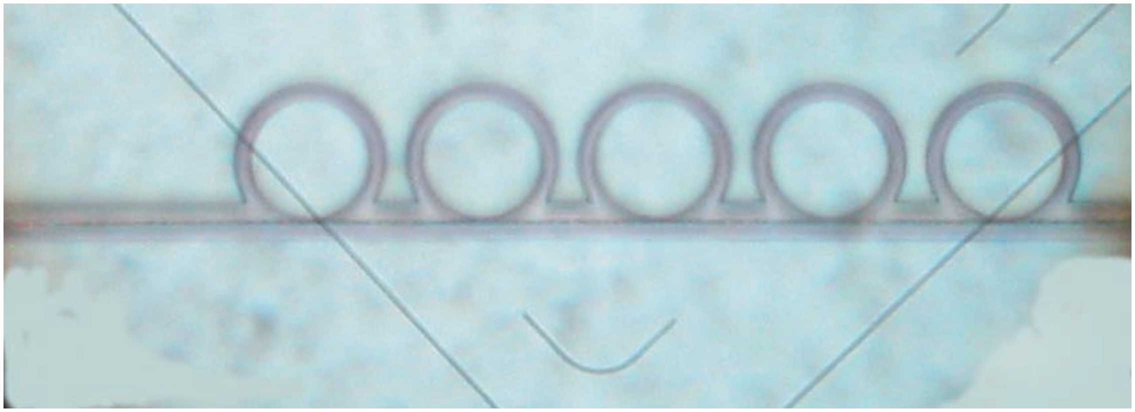
(distinction?)

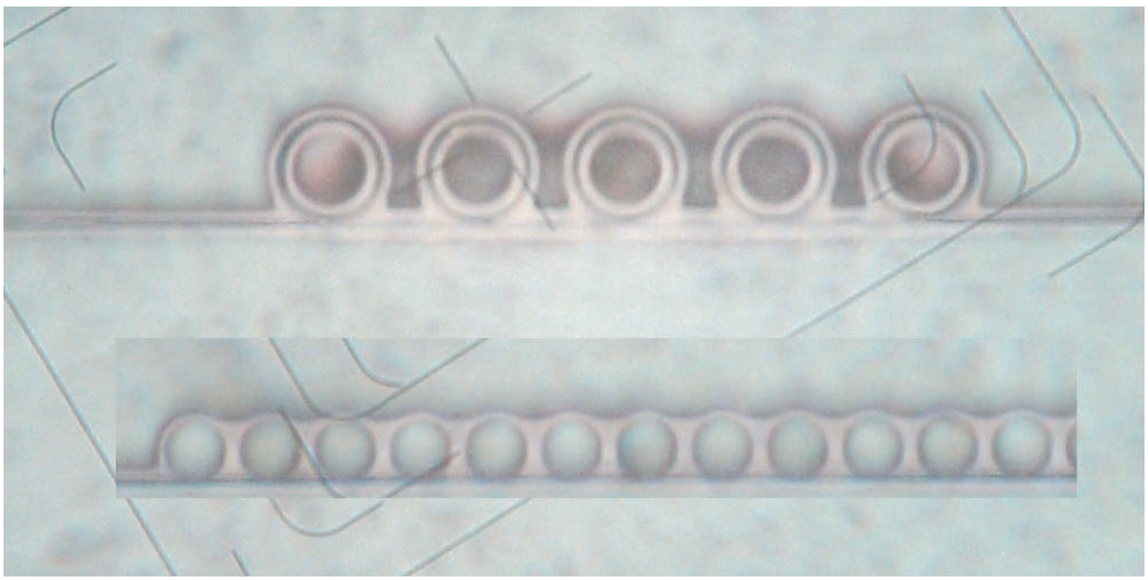
Disk Resonator and Optical Waveguide in PMMA Resist

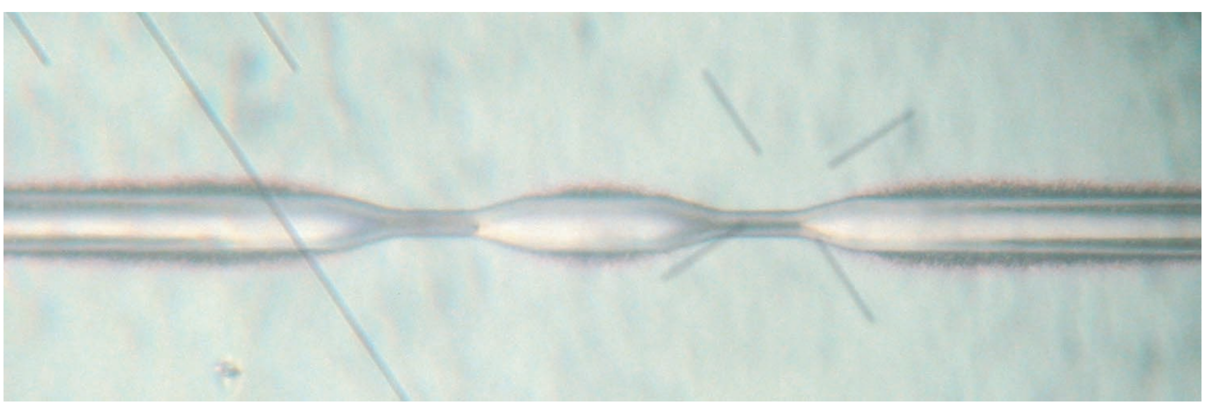


AFM

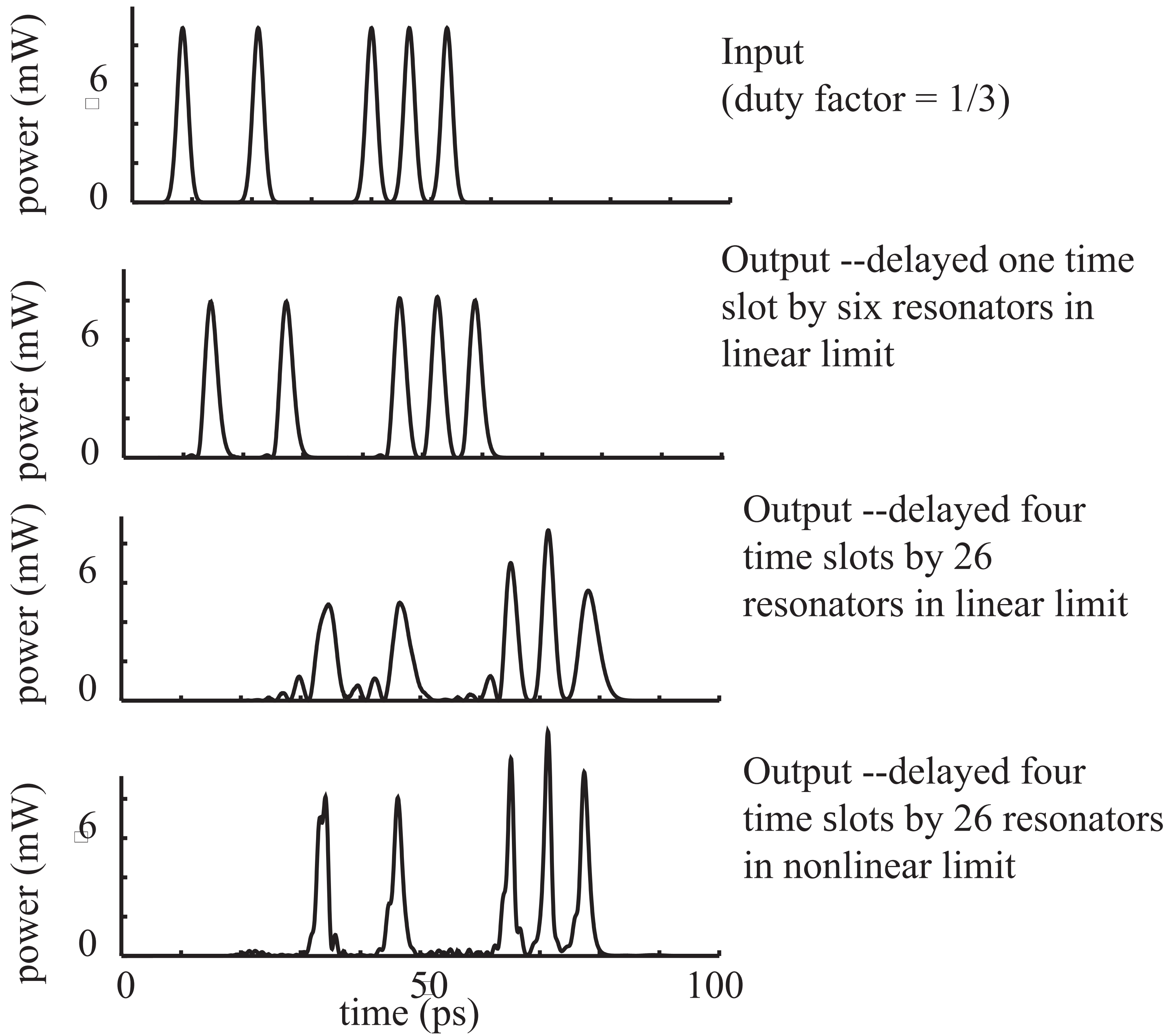
Photonic Devices in GaAs/AlGaAs





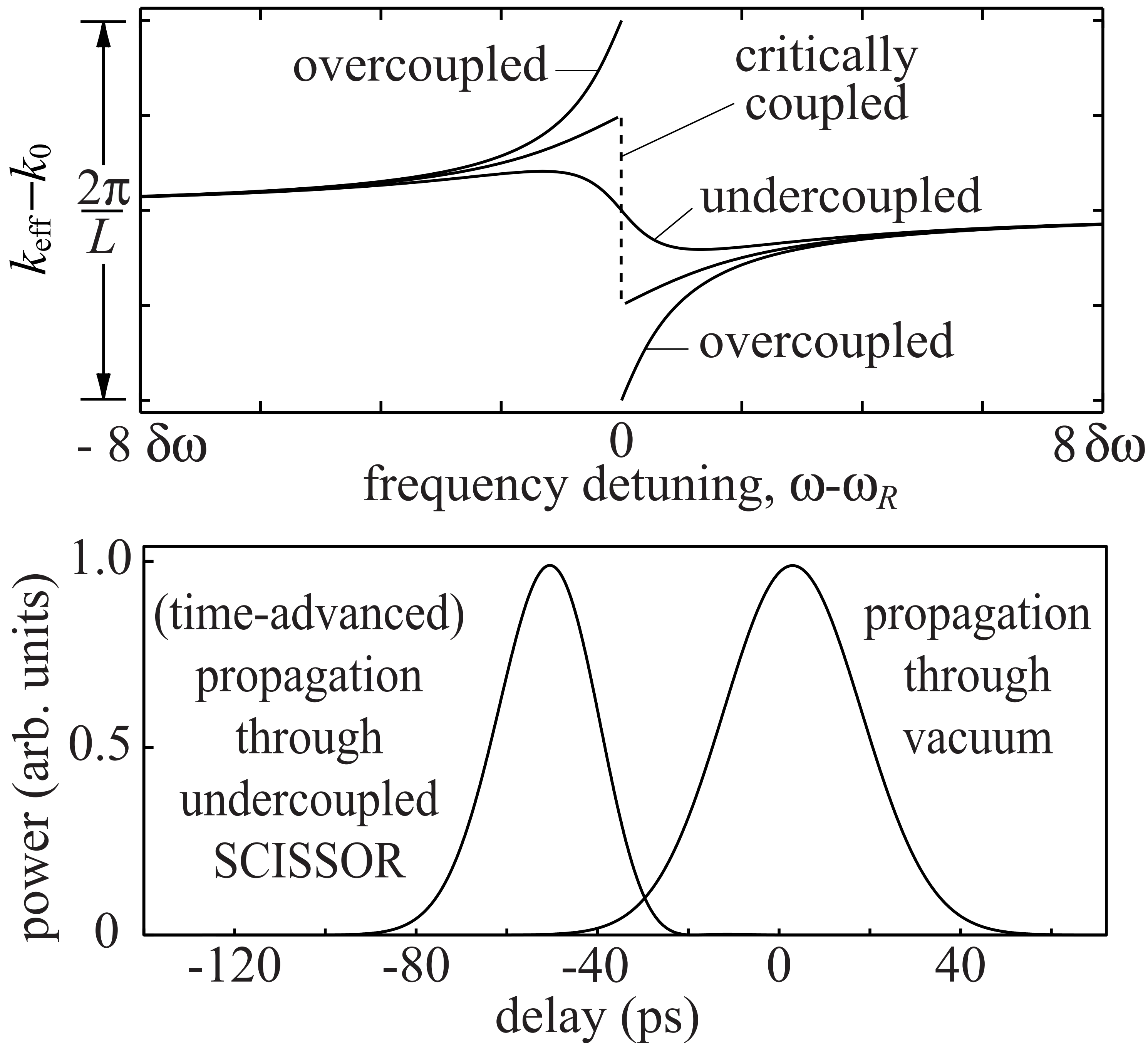


Performance of SCISSOR as Optical Delay Line

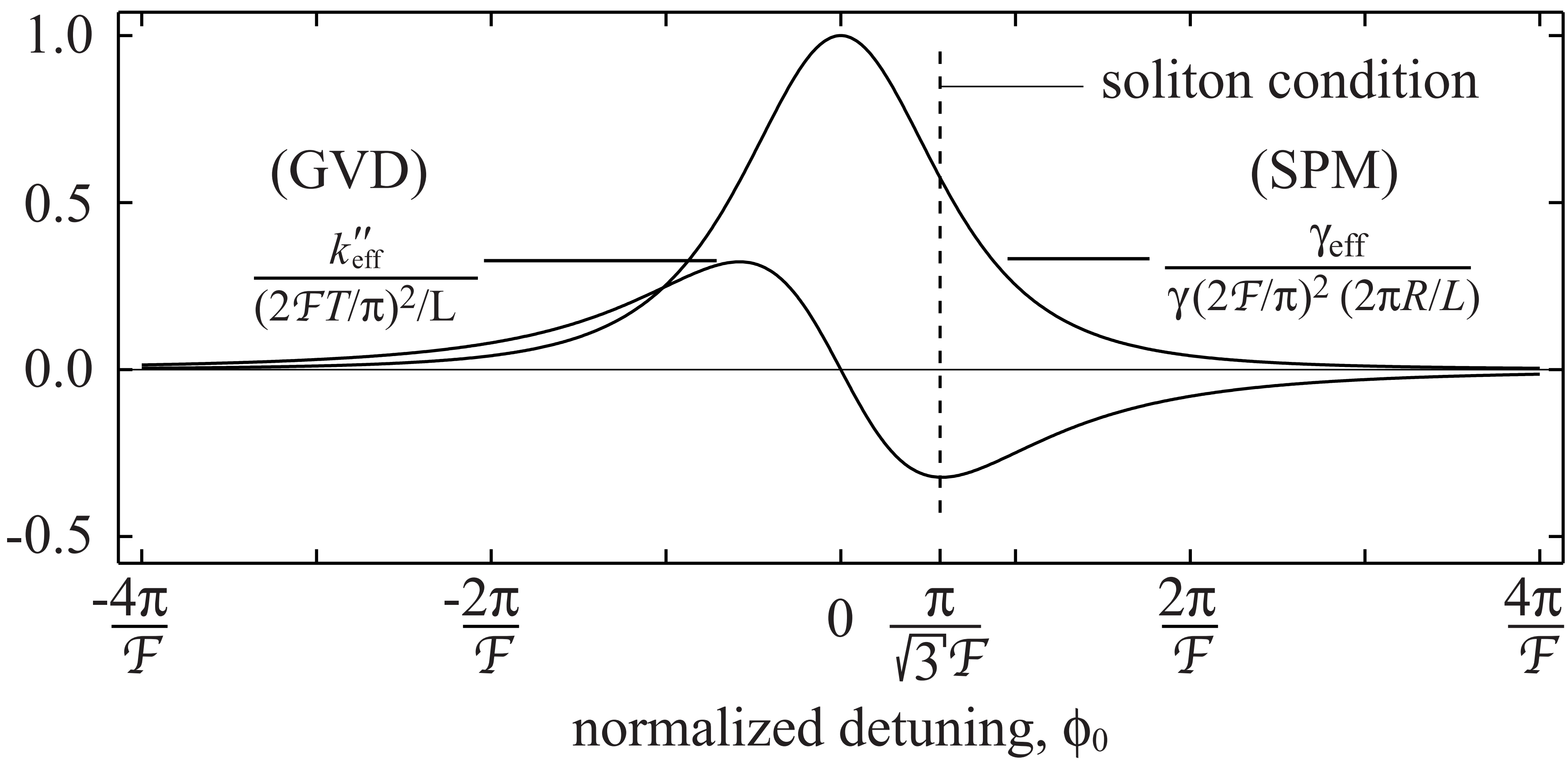


"Fast" (Superluminal) Light in SCISSOR Structures

Requires **loss** in resonator structure



Frequency Dependence of GVD and SPM Coefficients



Soliton Propagation

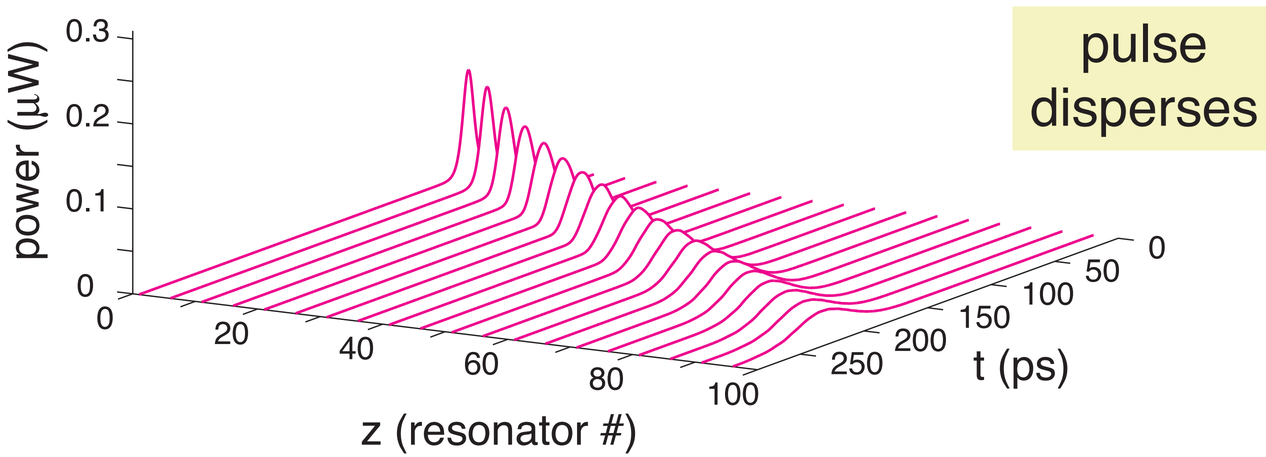
5 μm diameter resonators with a finesse of 30

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

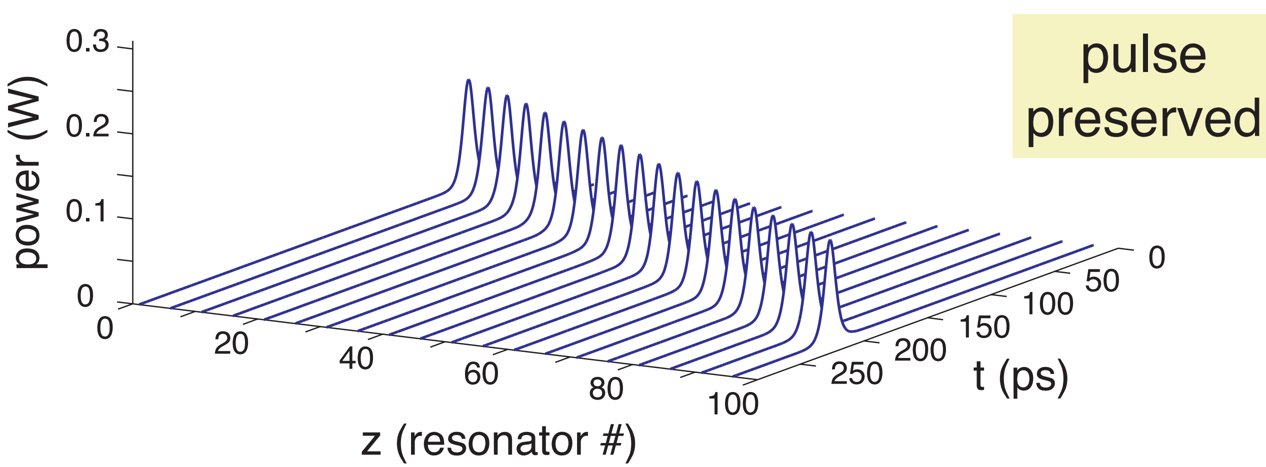
soliton may be excited via a 10 ps, 125mW pulse

simulation assumes a chalcogenide/GaAs-like nonlinearity

Weak Pulse

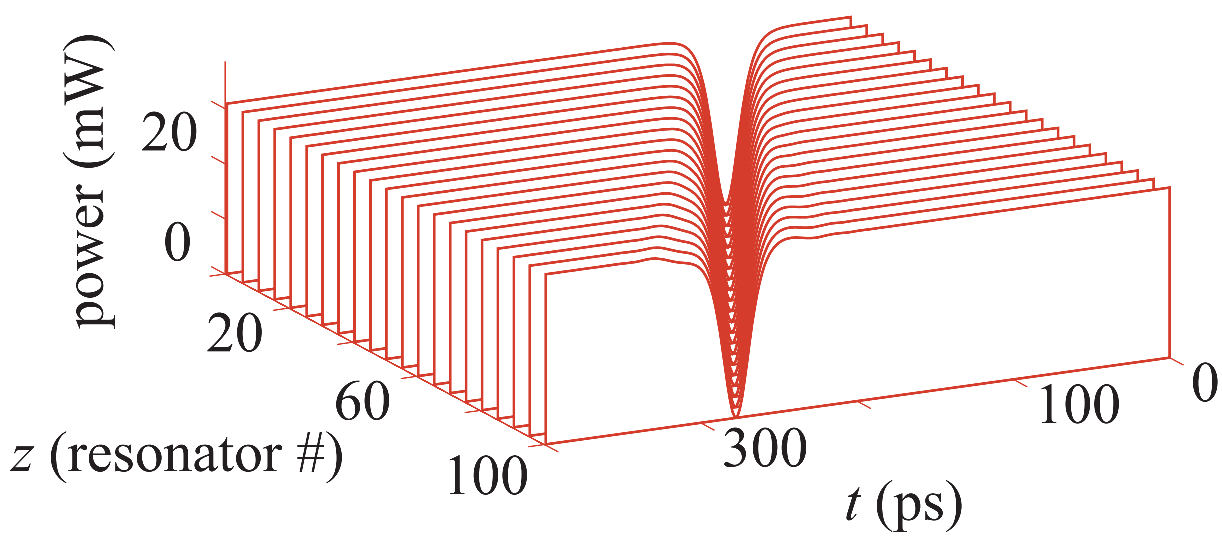


Fundamental Soliton

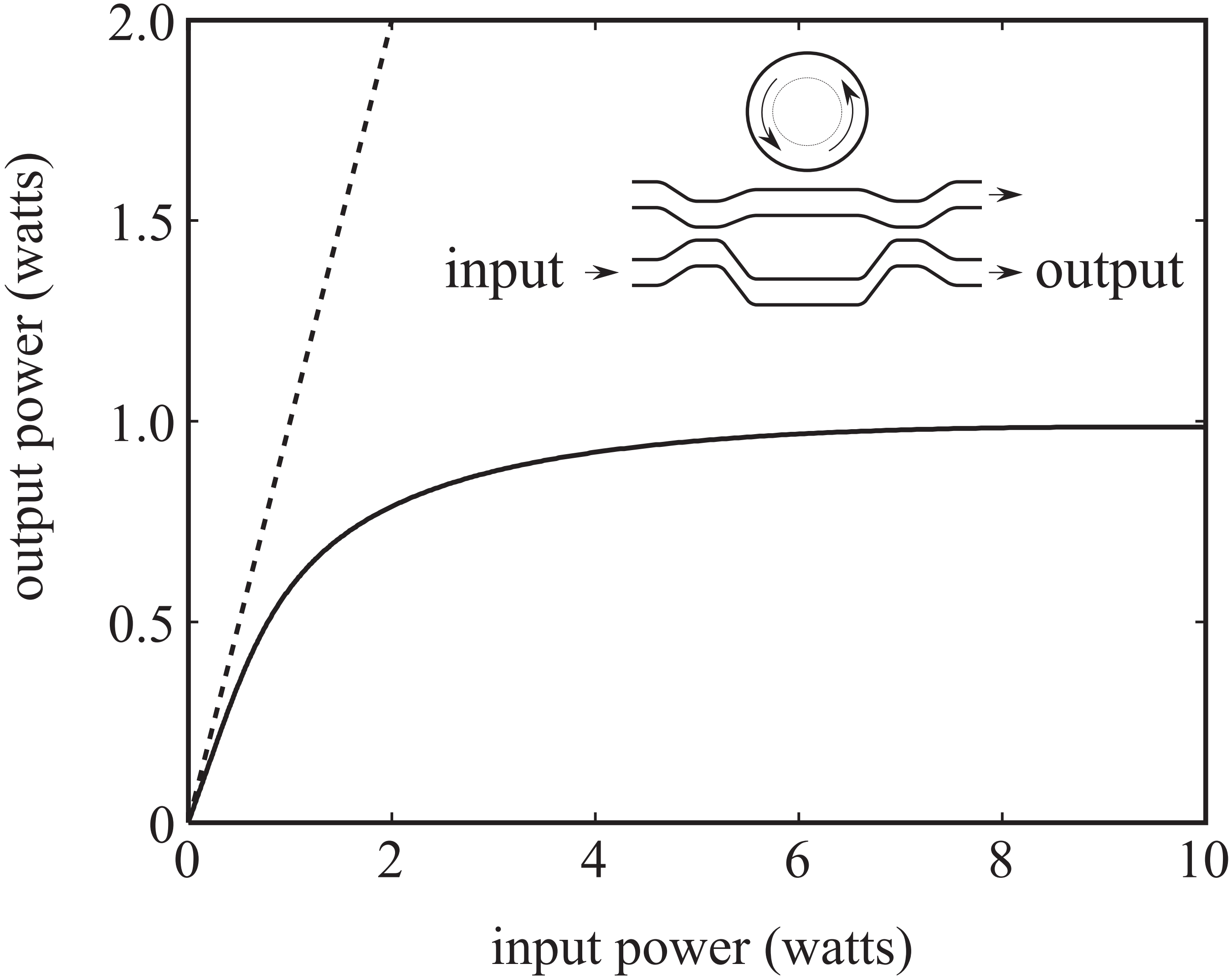


Dark Solitons

SCISSOR system also supports the propagation of dark solitons.



Optical Power Limiting in a Nonlinear Mach-Zenhder Interferometer



Photonic Devices for Biosensing

Objective:

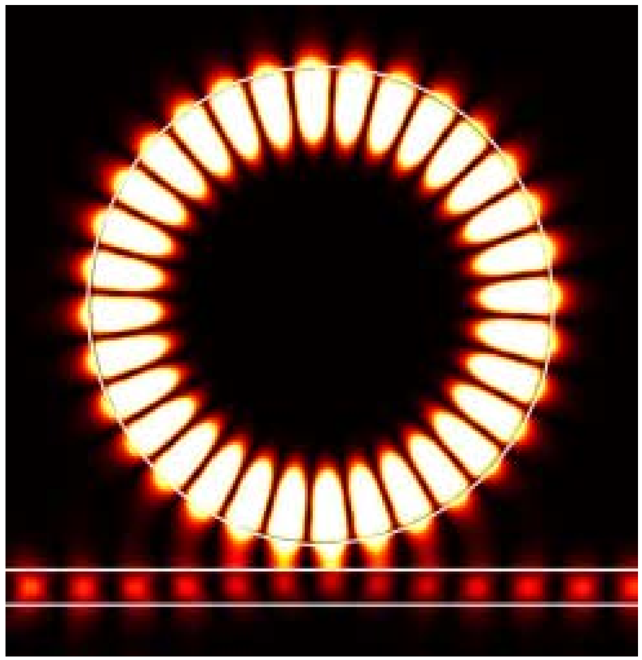
Obtain high sensitivity, high specificity detection of pathogens through optical resonance

Approach:

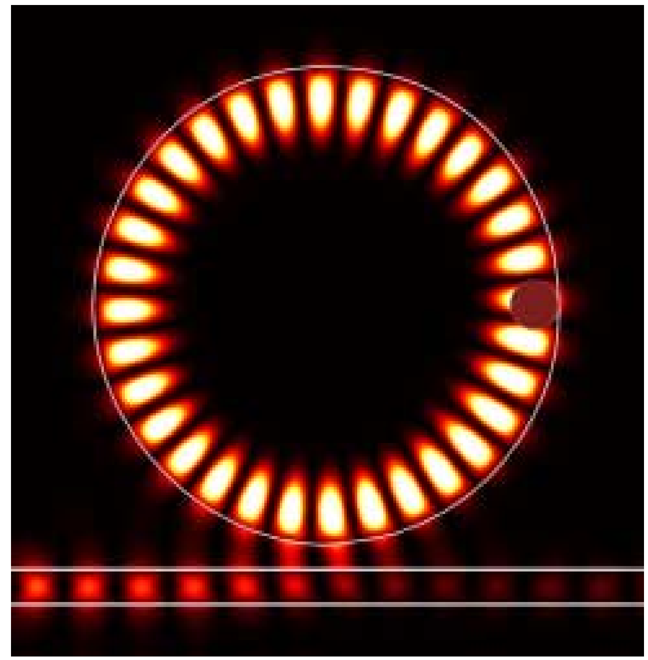
Utilize high-finesse whispering-gallery-mode disk resonator.

Presence of pathogen on surface leads to dramatic decrease in finesse.

Simulation of device operation:



Intensity distribution in absense of absorber.



Intensity distribution in presence of absorber.

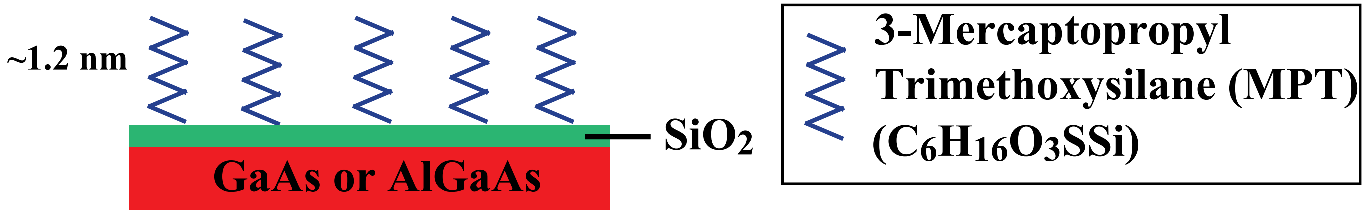
FDTD

Deposition of Surface Binding Layer

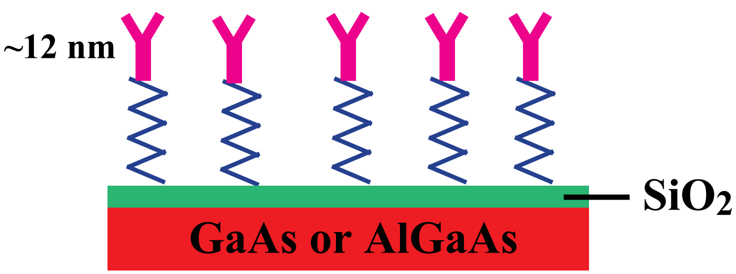
1) Bare device surface

2) SiO_2 layer deposited by PECVD

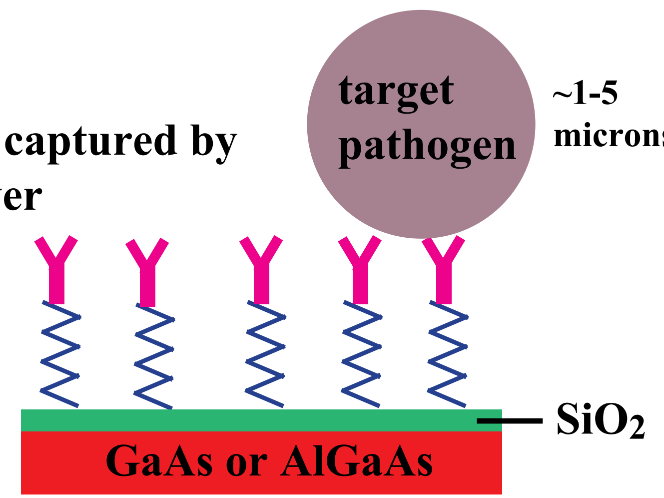
3) Silane coupling agent deposited on surface



4) Antibodies washed over surface / adhere to MPT



5) Pathogen captured by antibody layer



Demonstration of Selective Binding onto GaAs

g a

g a

g a

g a

n N

RN c

u r c c

Summary

Artificial materials hold great promise for applications in photonics because of

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

Demonstration of slow light propagation in ruby

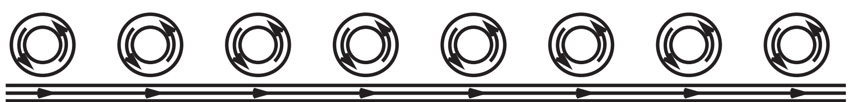
Thank you for your attention.

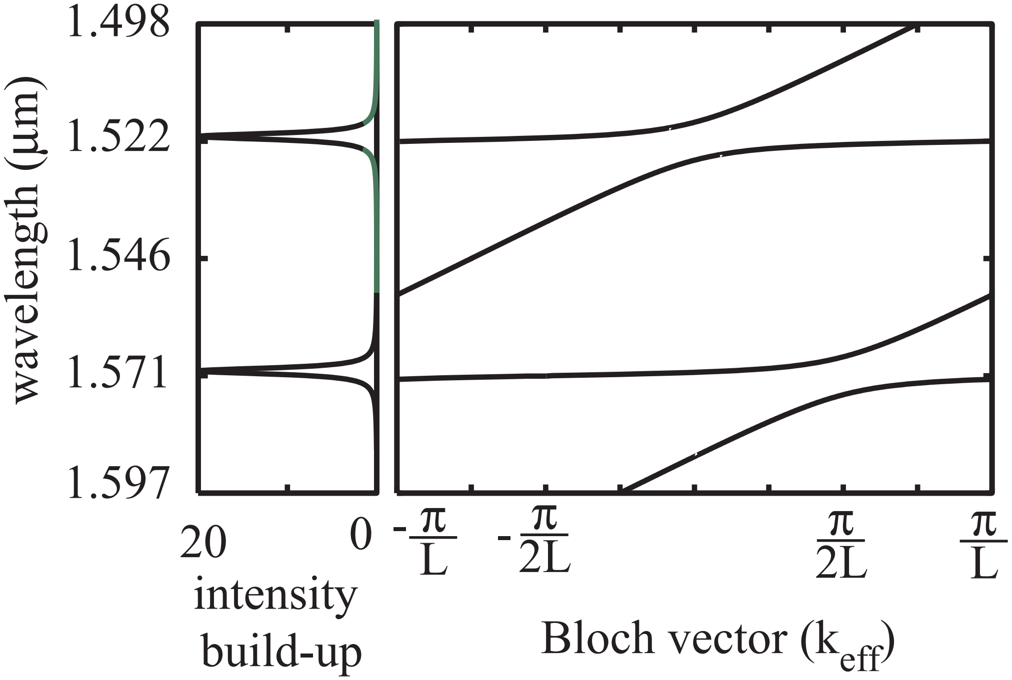
SCISSOR Dispersion Relations

Single-Guide SCISSOR

No bandgap

Large intensity buildup

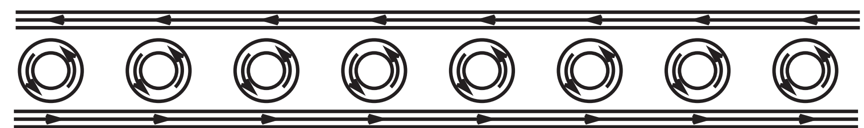


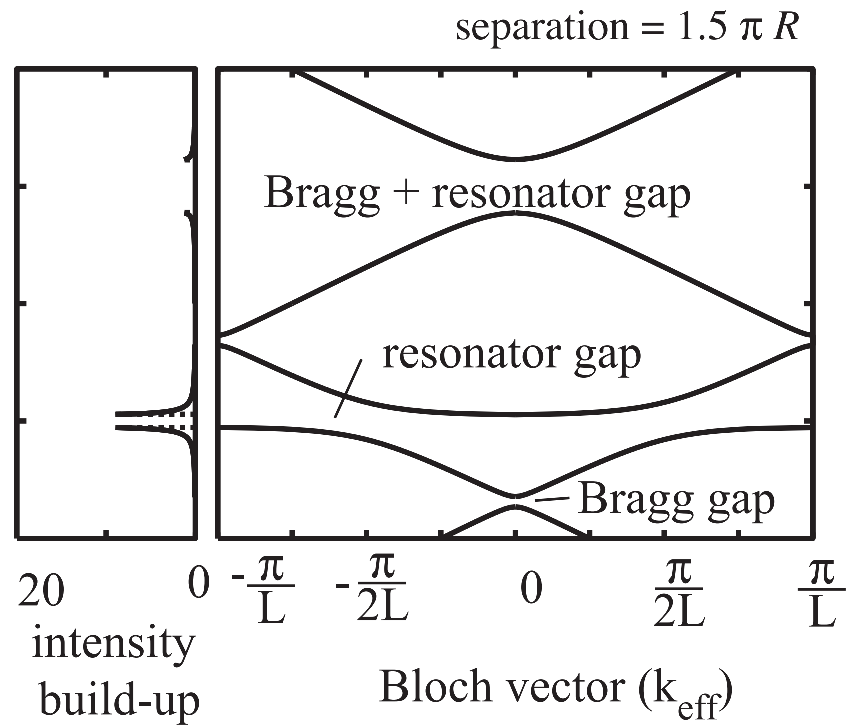


Double-Guide SCISSOR

Bandgaps occur

Reduced intensity buildup





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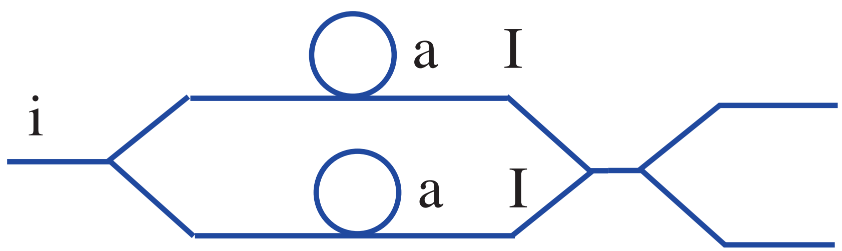

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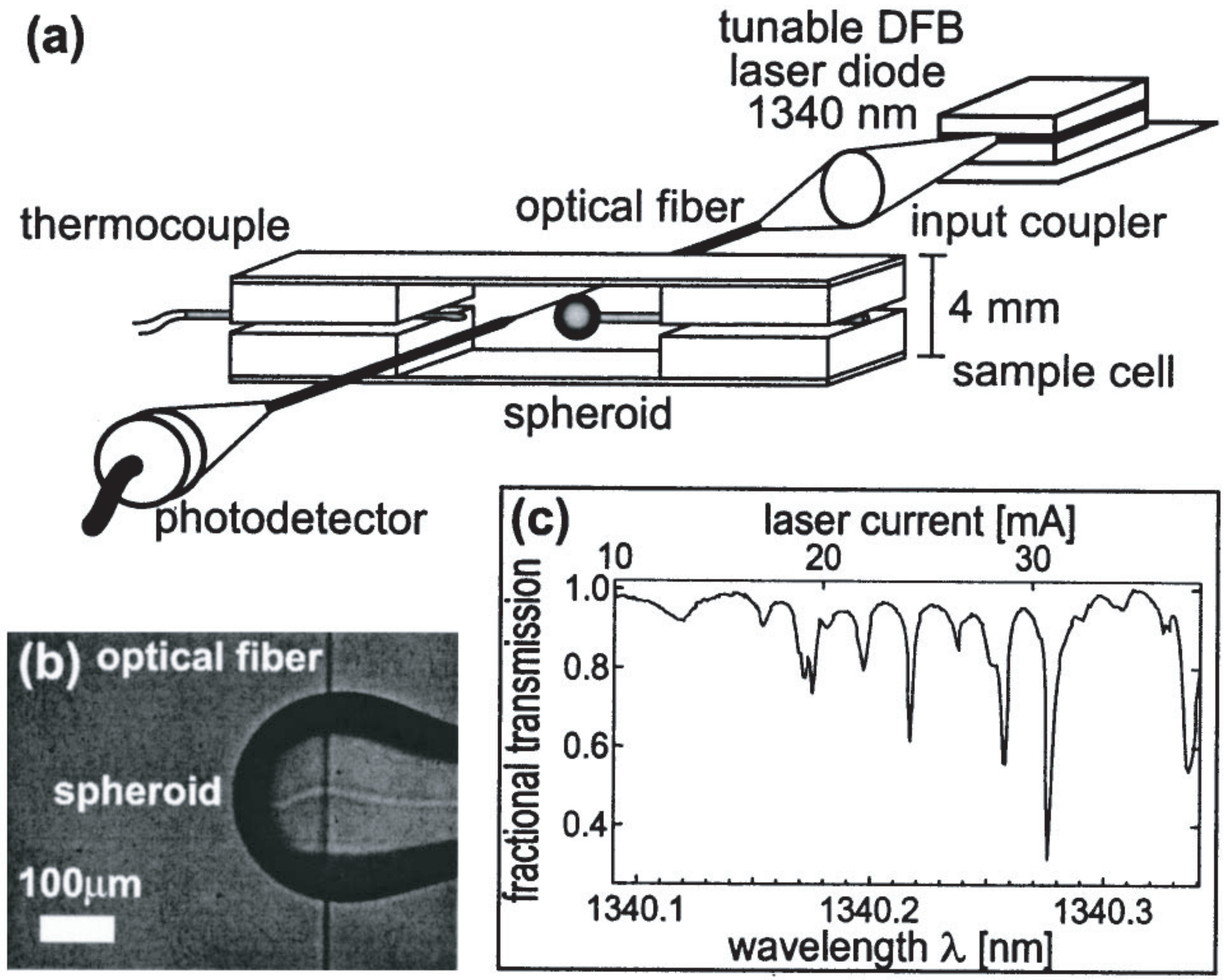


v La p l PLTP PP I

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

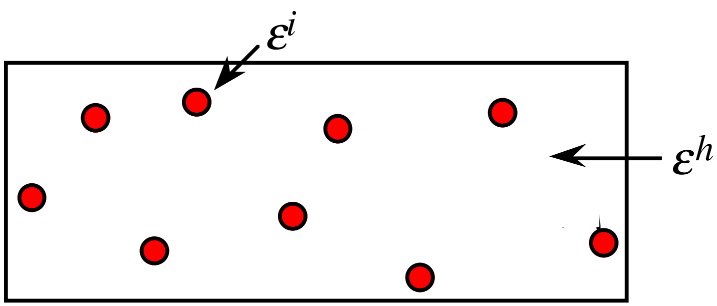
- New chemical compounds
- Quantum coherence (EIT, etc.)
- Composite Materials:
  (a) Microstructured Materials, e.g.
  Photonic Bandgap Materials,
  Quasi-Phasematched Materials, etc

  (b) Nanocomposite Materials

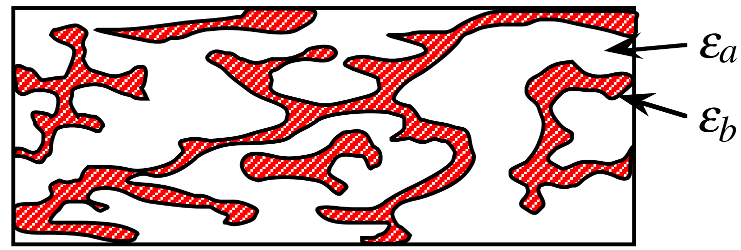
These approaches are not incompatible and in fact can be exploited synergistically!

Nanocomposite Materials for Nonlinear Optics

- Maxwell Garnett

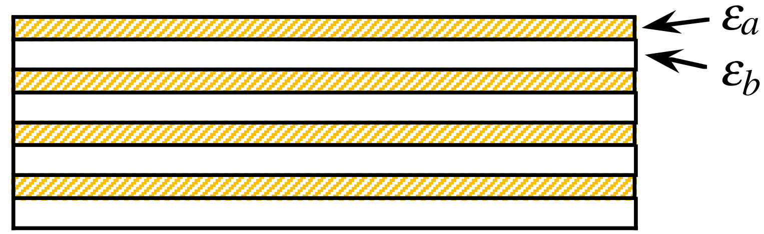


- Bruggeman (interdispersed)



- Fractal Structure

- Layered



scale size of inhomogeneity << optical wavelength

Gold-Doped Glass

A Maxwell-Garnett Composite

gold volume fraction approximately 10^{-6}

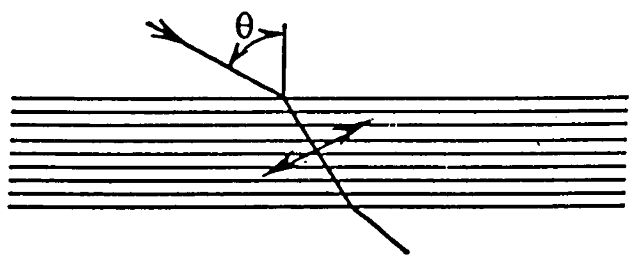
gold particles approximately 10 nm diameter

- Composite materials can possess properties very different from their constituents.

- Red color is because the material absorbs very strongly at the surface plasmon frequency (in the blue) -- a consequence of local field effects.

Demonstration of Enhanced NLO Response

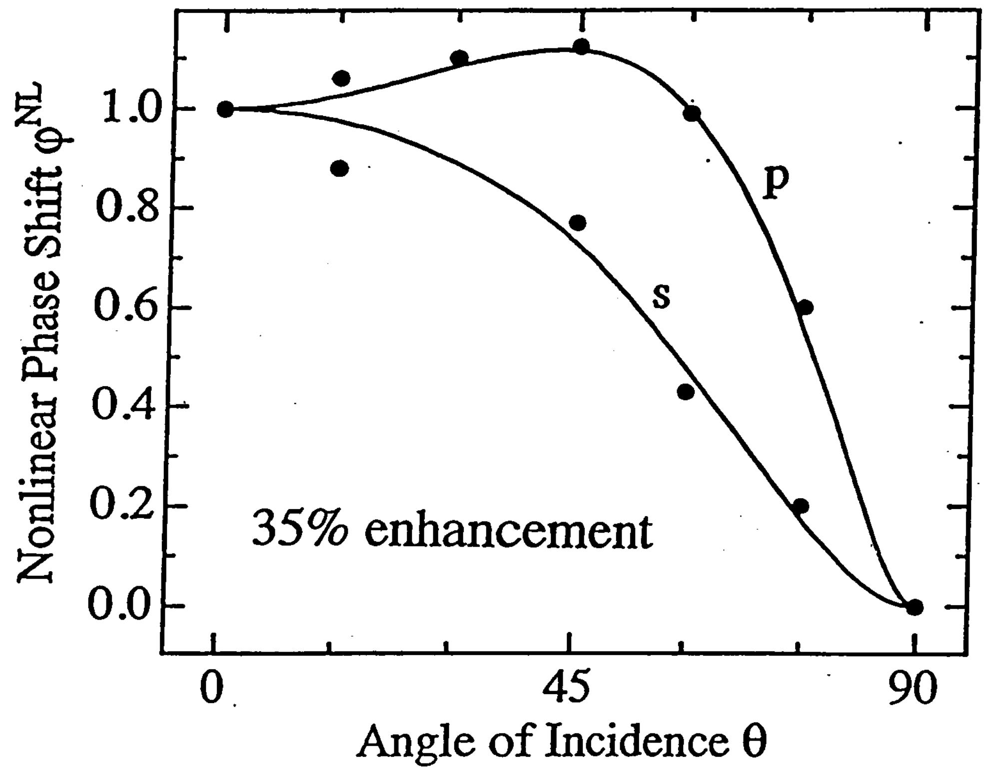
- Alternating layers of TiO_2 and the conjugated polymer PBZT.



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

Thus field is concentrated in *lower* index material.

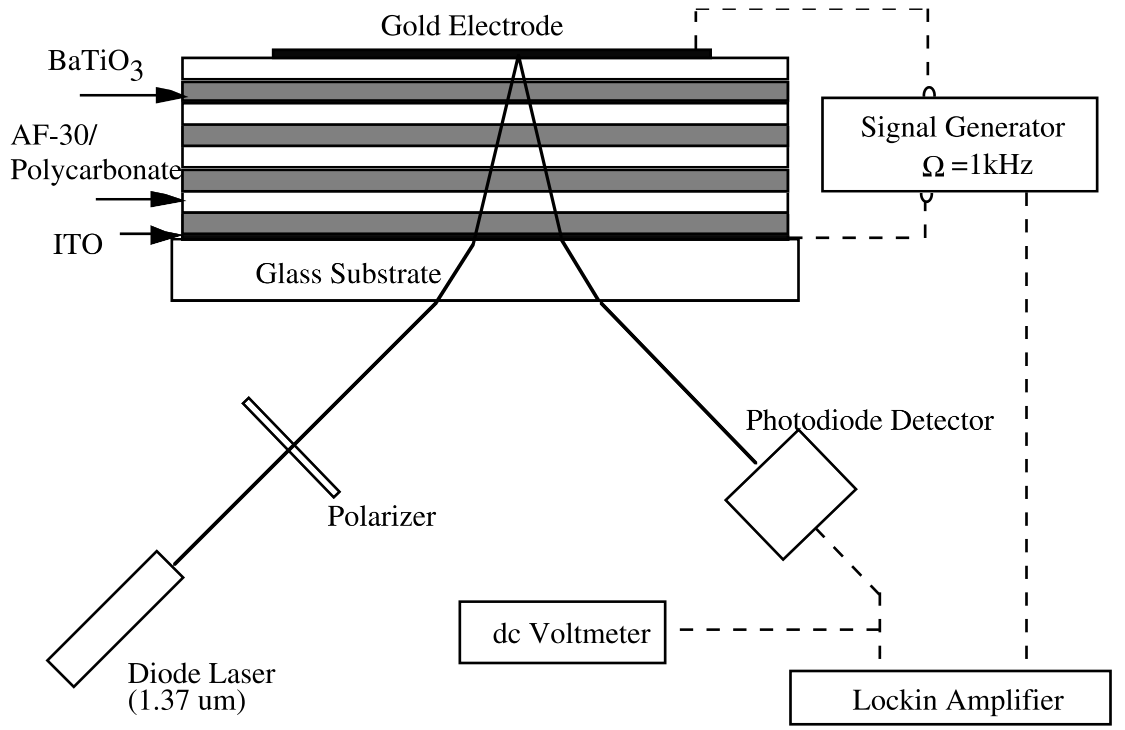
- Measure NL phase shift as a function of angle of incidence



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



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

- AF-30 (10%) in polycarbonate (spin coated)

  n=1.58 ε(dc) = 2.9

- barium titante (rf sputtered)

  n=1.98 ε(dc) = 15

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

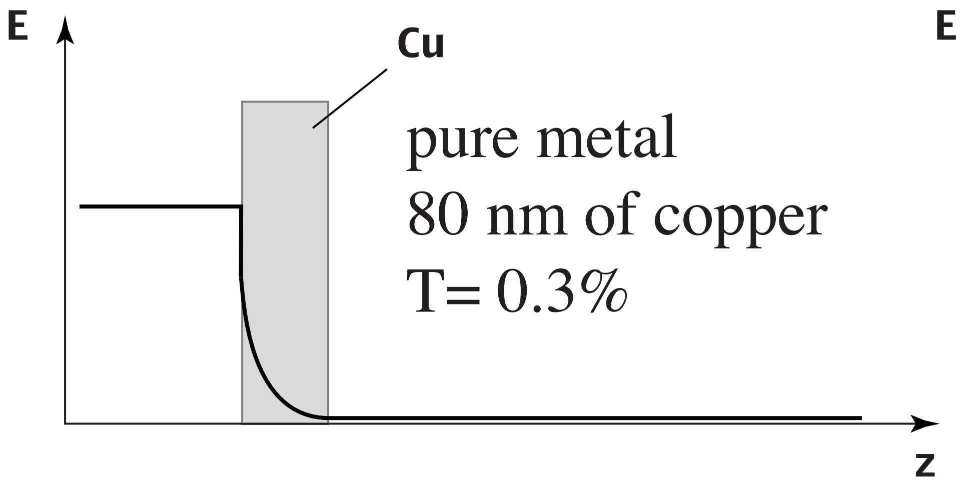
$$\approx 3.2\ \chi_{zzzz}^{(3)}(\text{AF-30 / polycarbonate})$$

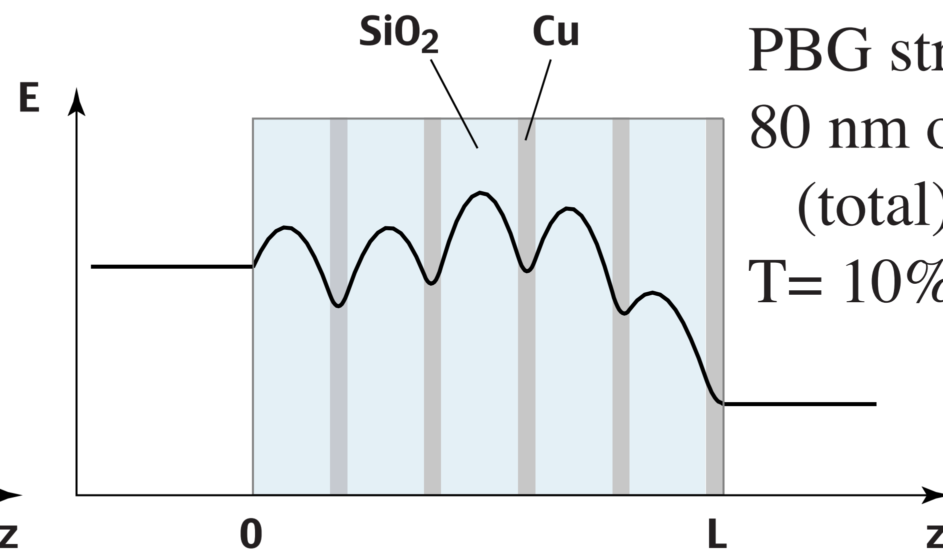
3.2 times enhancement in agreement with theory

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)





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

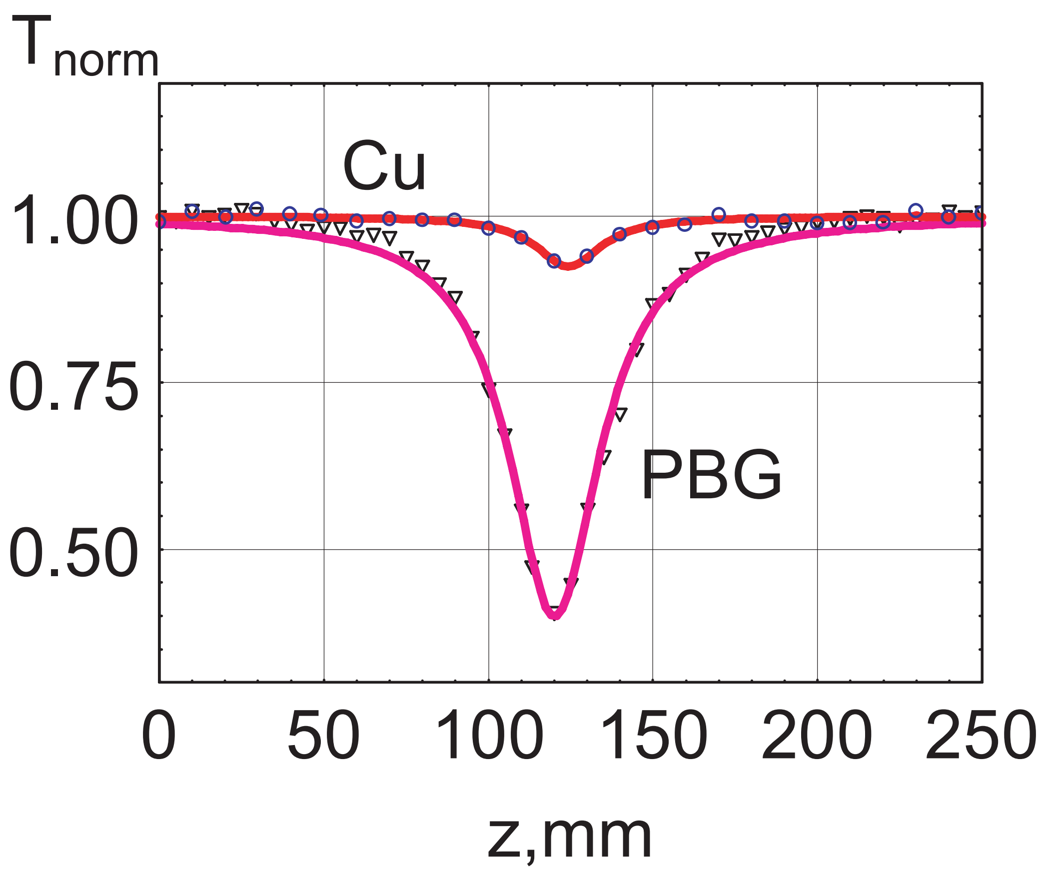
40 times enhancment of NLO response is predicted!

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

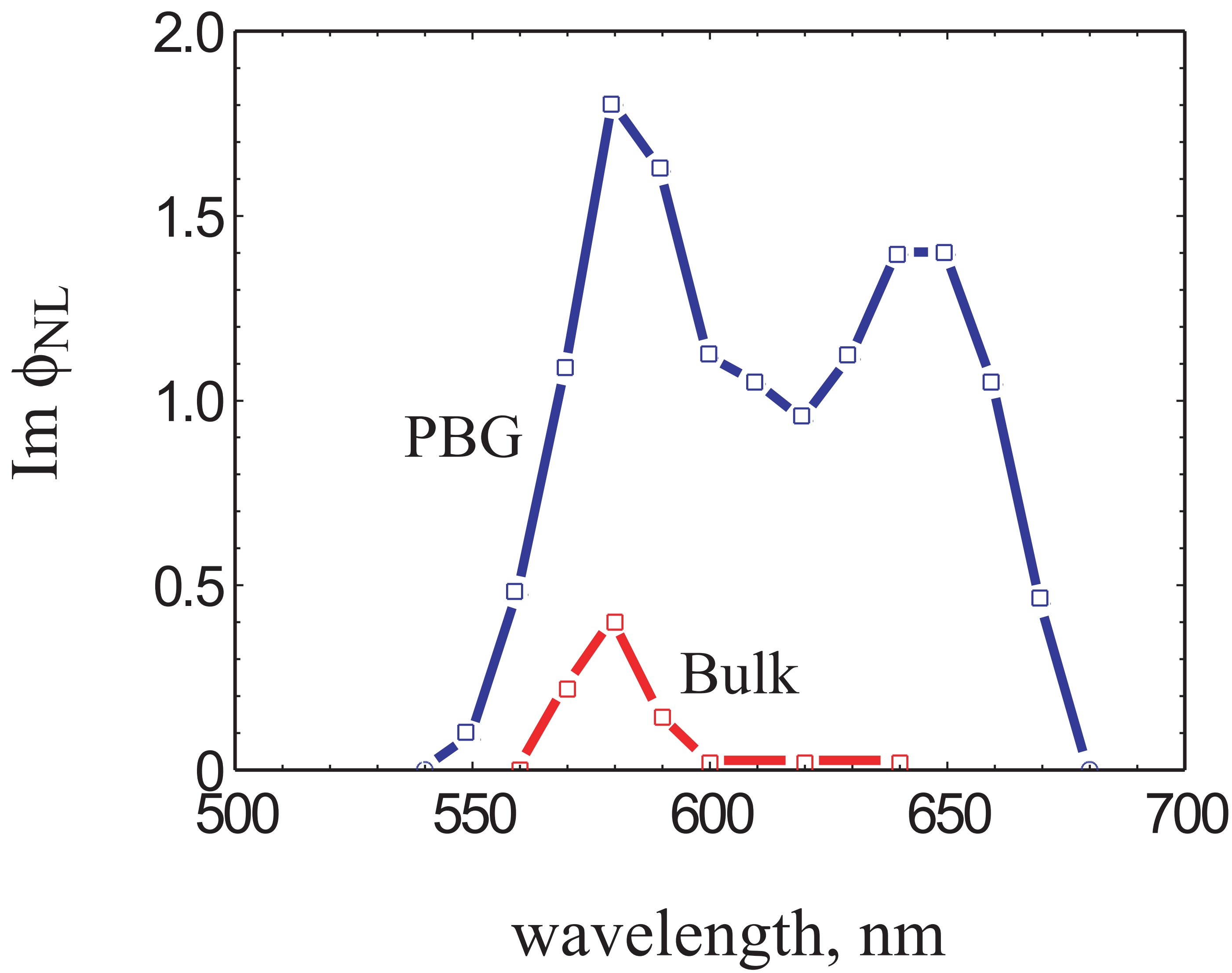
Open-aperture Z-scan
(measures Im $\chi^{(3)}$)

I = 500 MW/cm^2
λ = 640 nm



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

Spectral Dependence of the Nonlinear Response



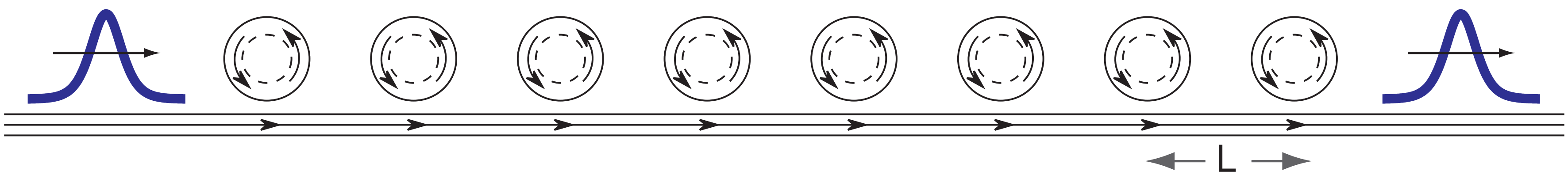
OPG:

$t = 25$ ps

$Q = 2$ to 5 mJ

$I \cong 100$ MW/cm^2

Propagation Equation for a SCISSOR



By arranging a spaced sequence of resonators, side-coupled to an ordinary waveguide, one can create an effective, structured waveguide that supports pulse propagation in the NLSE regime.

Propagation is unidirectional, and there is NO photonic bandgap to produce the enhancement. Feedback is intra-resonator and not inter-resonator.

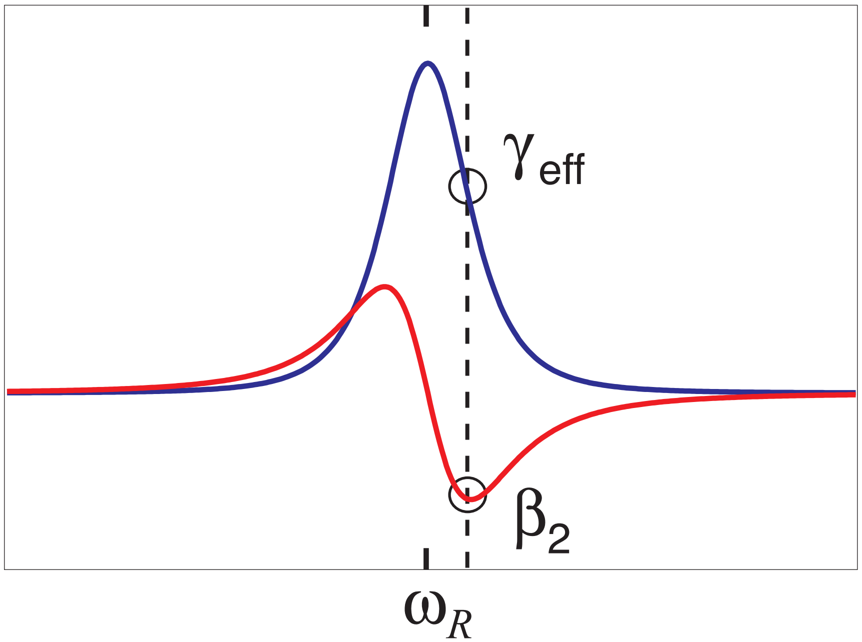
Nonlinear Schrödinger Equation (NLSE)

$$\frac{\partial}{\partial z}A = -i\frac{1}{2}\beta_2\frac{\partial^2}{\partial t^2}A + i\gamma|A|^2A$$

Fundamental Soliton Solution

$$A(z,t) = A_0\,\mathrm{sech}\left(\frac{t}{T_p}\right)e^{i\frac{1}{2}\gamma|A_0|^2 z}$$

Balancing Dispersion & Nonlinearity



soliton amplitude

$$A_0 = \sqrt{\frac{|\beta_2|}{\gamma\, T_p^2}} = \sqrt{\frac{T^2}{\sqrt{3}\,\gamma\, 2\pi R\, T_p^2}}$$

adjustable by controlling ratio of transit time to pulse width

Resonator-induced dispersion can be 5-7 orders of magnitude greater than the material dispersion of silica!

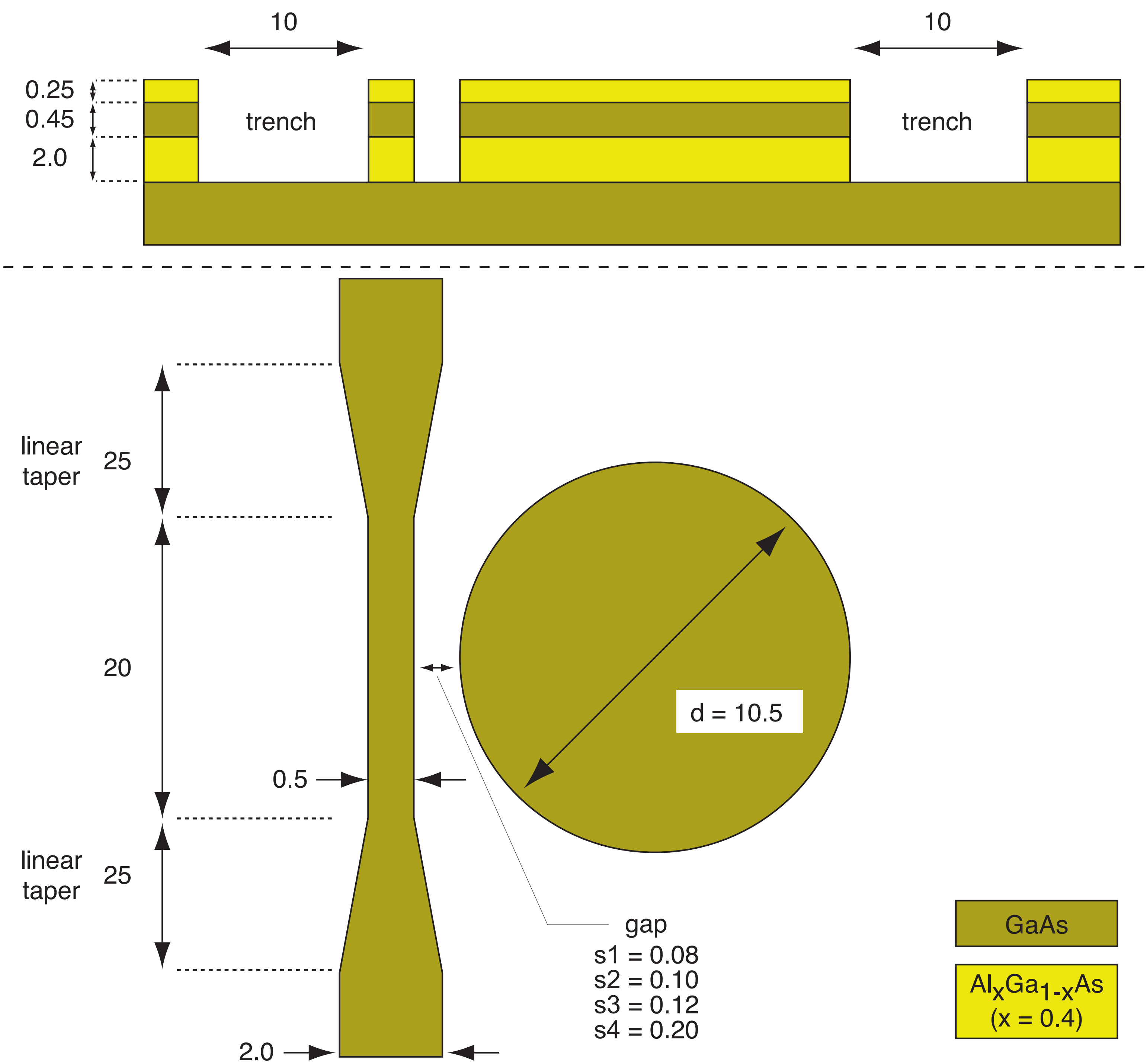
An enhanced nonlinearity may be balanced by an induced anomalous dispersion at some detuning from resonance to form solitons

Resonator enhancement of nonlinearity can be 3-4 orders of magnitude!

A characteristic length, the soliton period may as small as the distance between resonator units!

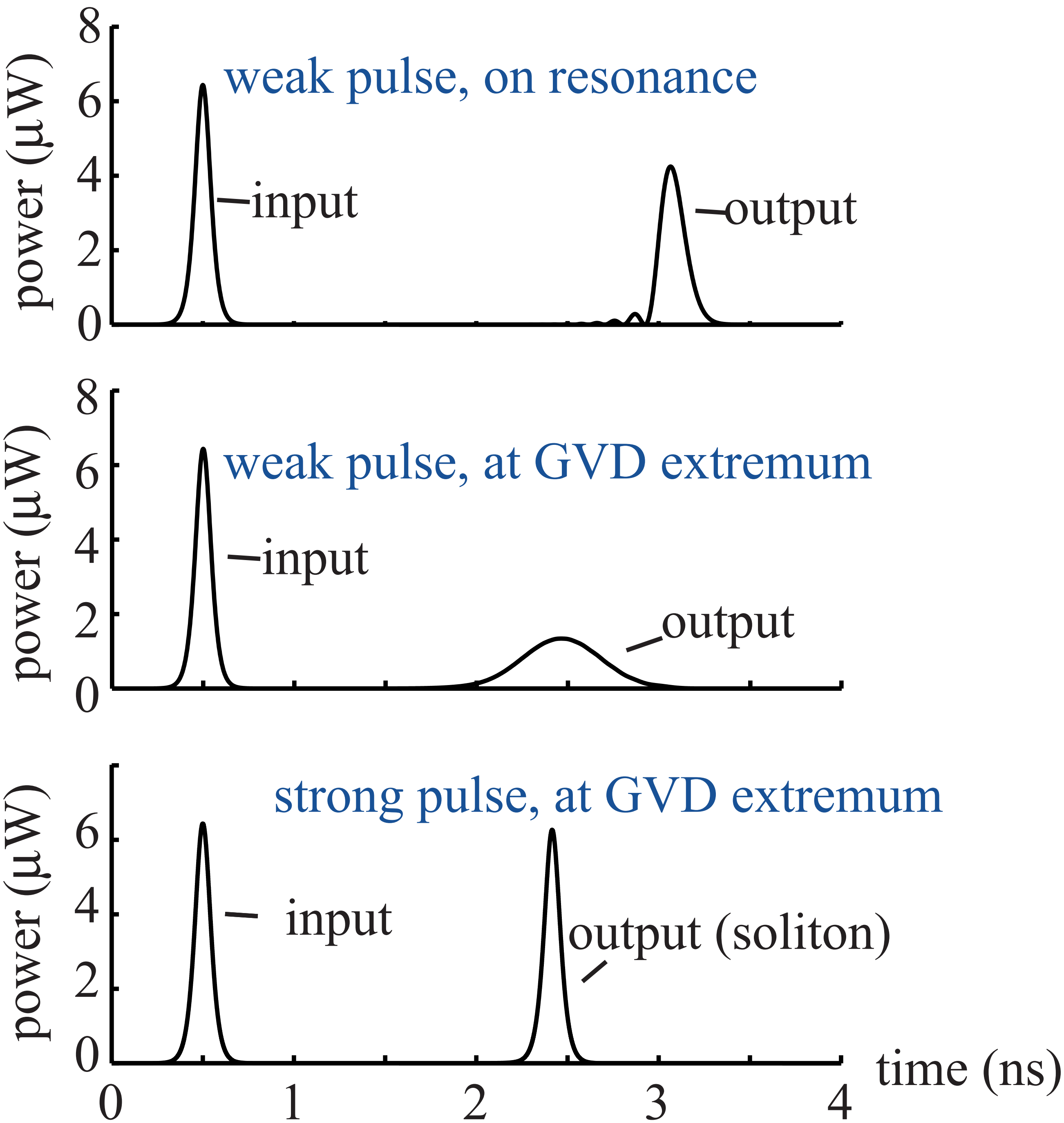
Microdisk Resonator Design

(Not drawn to scale)
All dimensions in microns



J. E. Heebner and R. W. Boyd

Pulse Distortion on Propagation through SCISSOR Structure



Maximum delay, but pulse distorted by higher-order dispersion.

Slightly reduced delay, no distortion, but spreading due to GVD.

Slightly reduced delay, no distortion, SPM compensates for spreading

Photonic Device Fabrication Procedure

(1) MBE growth

(2) Deposit oxide

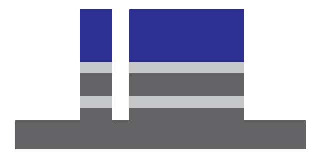
(3) Spin-coat e-beam resist

(4) Pattern inverse with e-beam & develop

(5) RIE etch oxide

(6) Remove PMMA

(7) CAIBE etch AlGaAs-GaAs

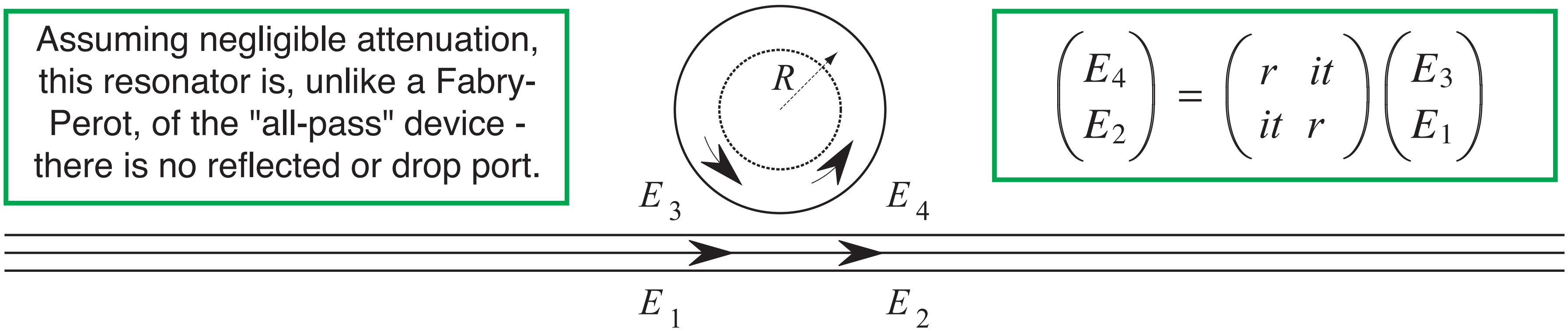


(8) Strip oxide

RWB - 10/4/01

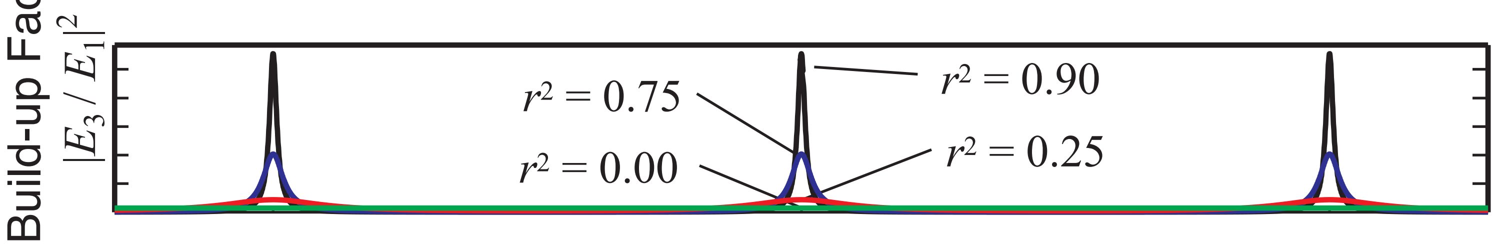
Properties of a Single Microresonator

Assuming negligible attenuation, this resonator is, unlike a Fabry-Perot, of the "all-pass" device - there is no reflected or drop port.

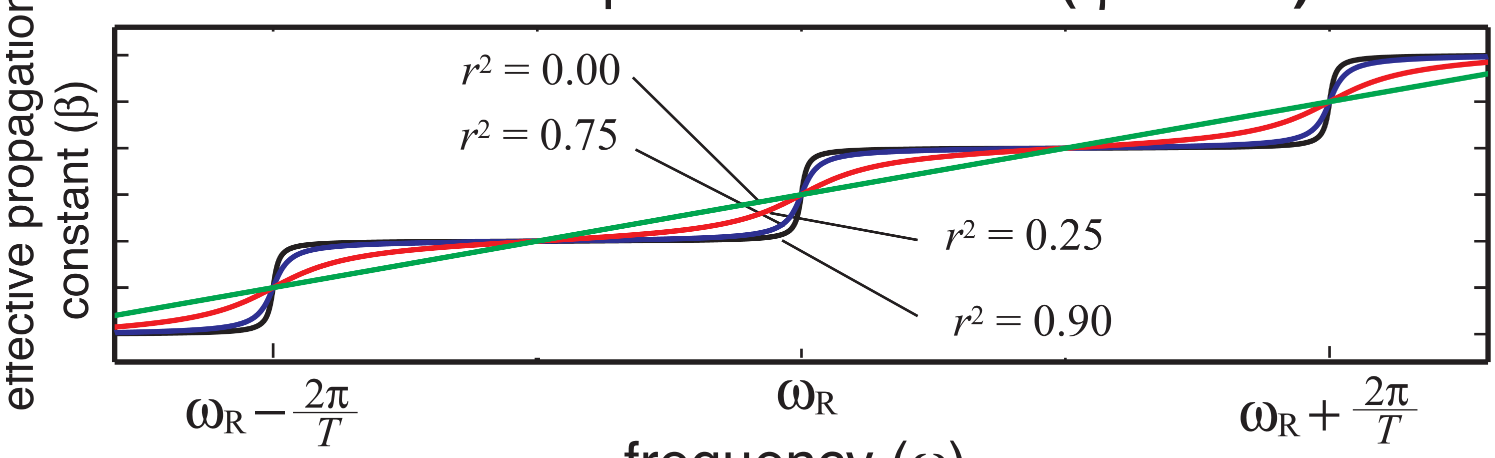


$$\begin{pmatrix} E_4 \\ E_2 \end{pmatrix} = \begin{pmatrix} r & it \\ it & r \end{pmatrix} \begin{pmatrix} E_3 \\ E_1 \end{pmatrix}$$

Intensity Enhancement ($|E_3 / E_1|^2$)



Modified Dispersion Relation (β vs. ω)



Definitions

Finesse

$$F = \frac{\pi}{1-r}$$

Transit Time

$$T = \frac{n 2\pi R}{c}$$