Slow Light in Ruby and in Artificial Materials

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E. Wolf, Progress in Optics 43

Chapter 6

"Slow" and "fast" light

by

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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

Challenge

Slow light in room-temperature solid-state material.

Prospectus

Fundamentals of slow light

Slow light in ruby

Slow light in artificial materials

Phase velocity $\neq$ group velocity

Phase Velocity

Monochromatic wave

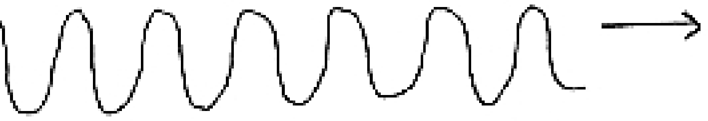
$$E(z,t) = A\, e^{i(kz-\omega t)} + cc$$

phase velocity $v_p = \omega/k$

If $k = 2\pi n/\lambda_0$, $\omega = 2\pi\nu$, $\nu = c/\lambda_0$

$$v_p = \frac{c}{n}$$

Why is phase velocity ω/k?



phase of wave $\phi = kz - \omega t$

Point of constant phase moves such that

$$k\,\Delta z = \omega\,\Delta t$$

Thus

$$v_p = \frac{\Delta z}{\Delta t} = \frac{\omega}{k}$$

Group Velocity

Pulse
(wave packet)

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

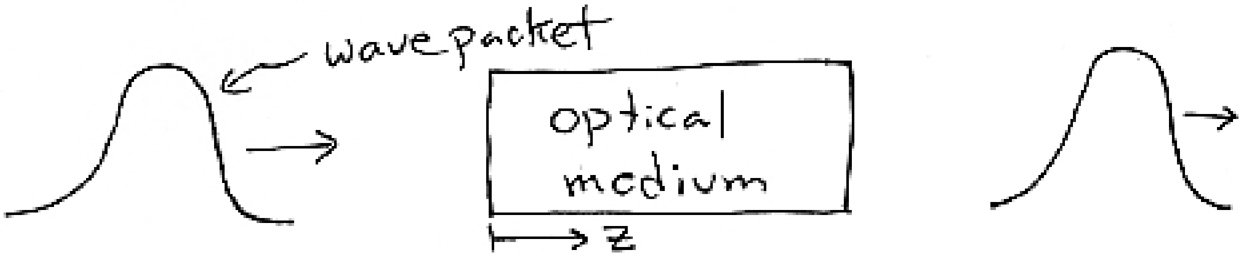
For $k = \frac{n\omega}{c}$. $\frac{dk}{d\omega} = \frac{1}{c}\left(n + \omega \frac{dn}{d\omega}\right)$

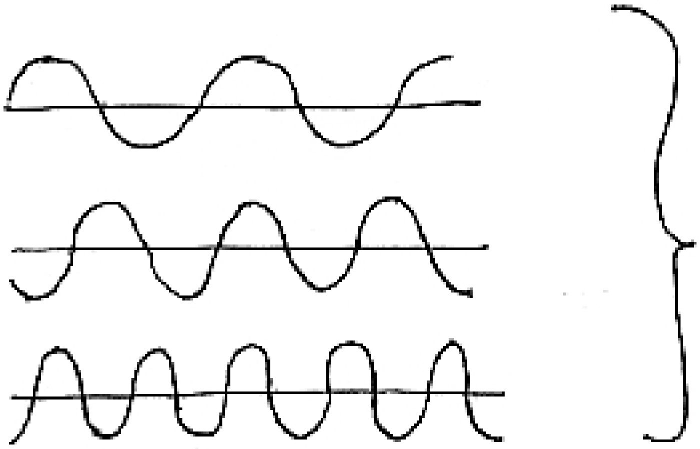
Thus

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

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

Why is $v_g = \frac{d\omega}{dk}$?





various frequency components add in phase at peak of pulse

Want components to add in phase for <u>all</u> z.

Phase $\phi = n\omega z/c - \omega t$

Want no change of ϕ with ω.

$$\frac{d\phi}{d\omega} = \frac{dn}{d\omega}\frac{\omega z}{c} + \frac{nz}{c} - t = 0$$

or

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

- Want v_g very different from v_p

Need very large dispersion

Study resonances of atomic vapor

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

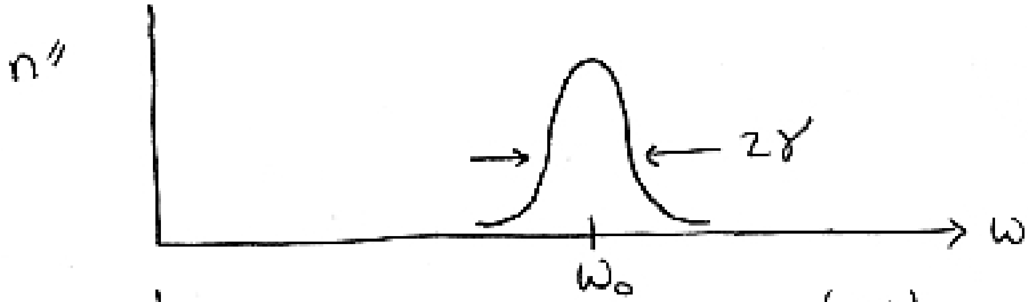
Light Propagation in Atomic Vapors

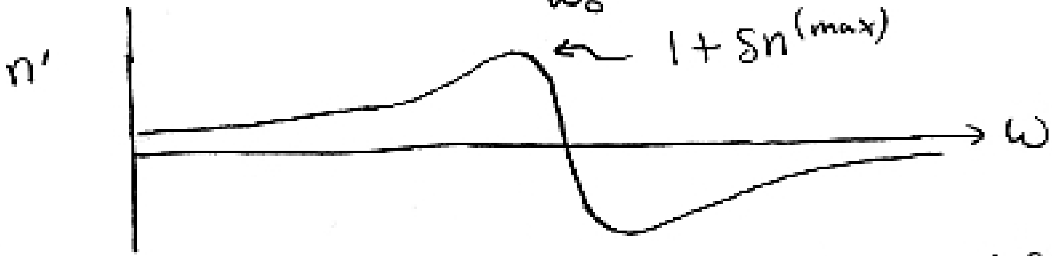
$$n = \sqrt{\varepsilon} = \sqrt{1 + 4\pi\chi} \qquad \chi = \frac{Ne^2/2m\omega_0}{(\omega_0 - \omega) - i\gamma}$$

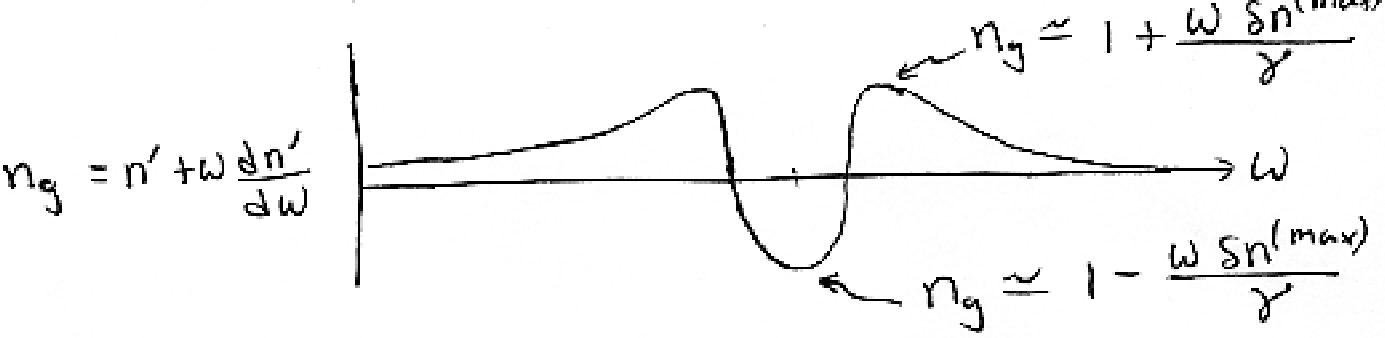
For N not too large $\quad n = n' + in'' \simeq 1 + 2\pi\chi$

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

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







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

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

(But with 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 Ruby

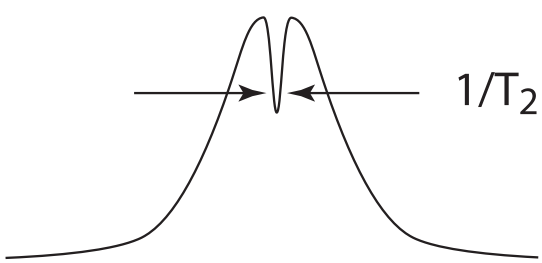
Need a large $dn/d\omega$. (How?)

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

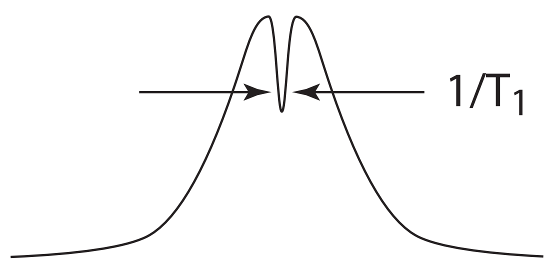
Well-known (to the few people how know it well) how to do so:

Make use of “spectral holes” due to population oscillations.

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



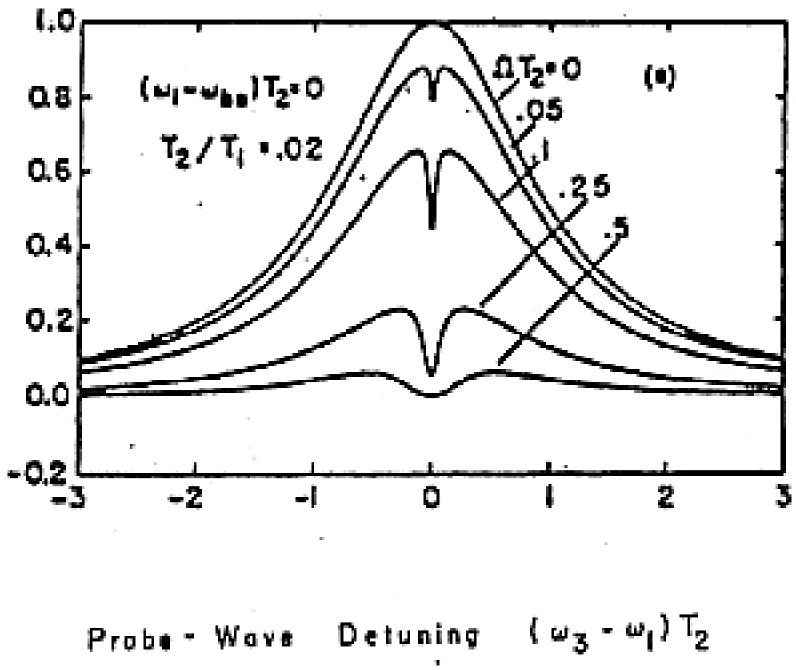
inhomogeneously broadened medium



homogeneously broadened medium (or inhomogeneously broadened)

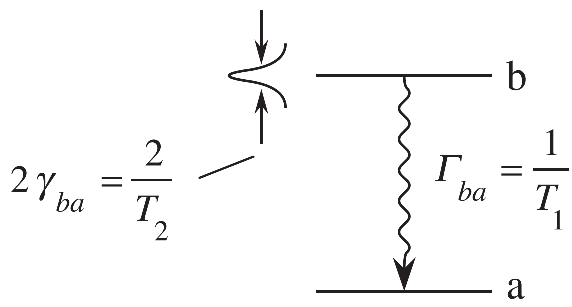
Spectral Holes in Homogeneously Broadened Materials

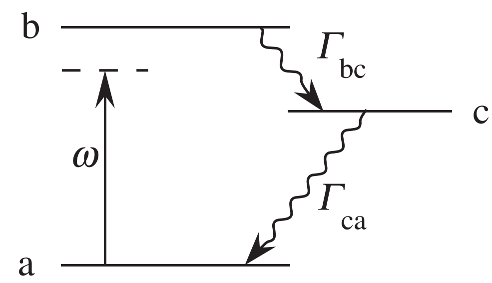
Occurs only in collisionally broadened media ($T_2 << T_1$)

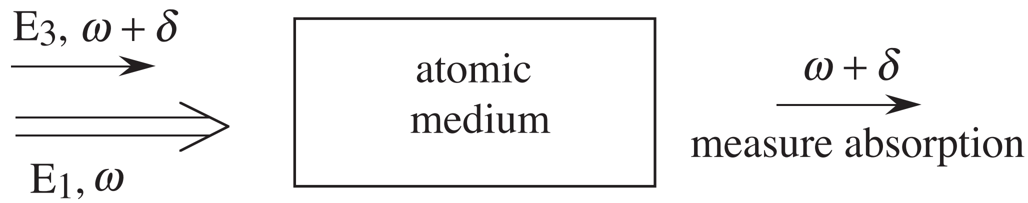


Boyd, Raymer, Narum and Harter, Phys. Rev. A24, 411, 1981.

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 $\delta \leq 1/T_1$

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

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

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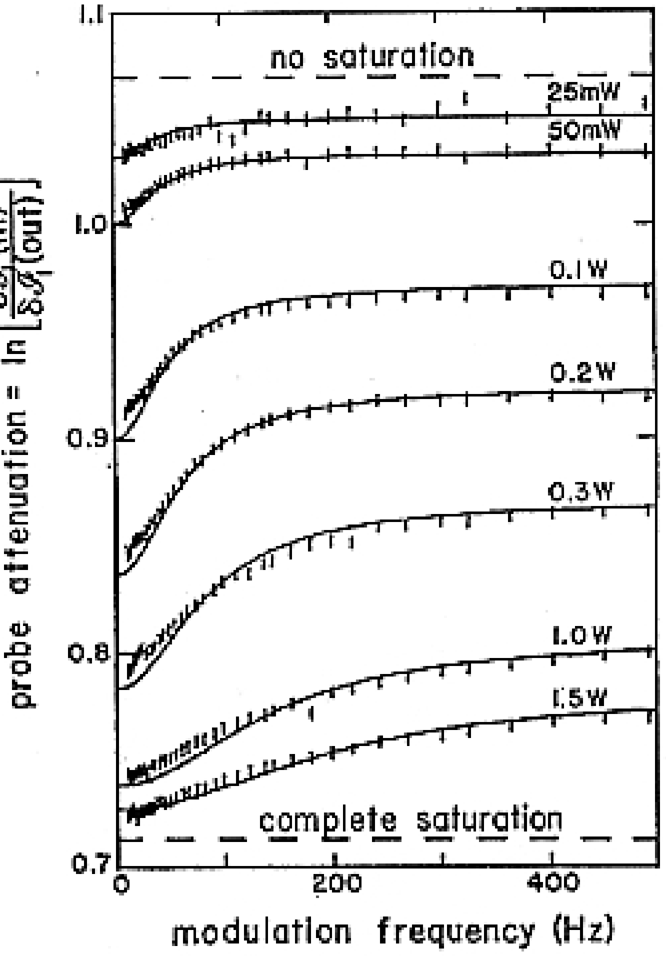
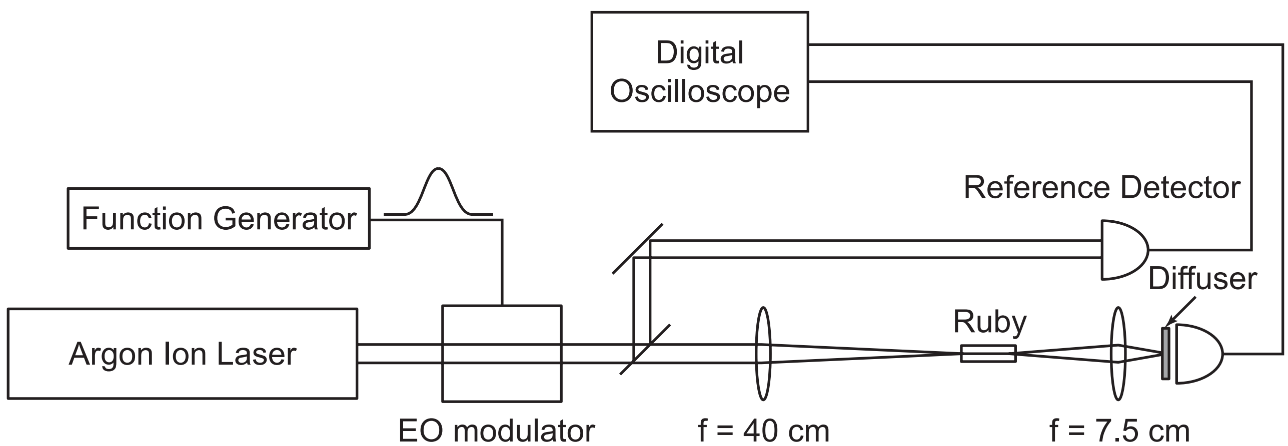


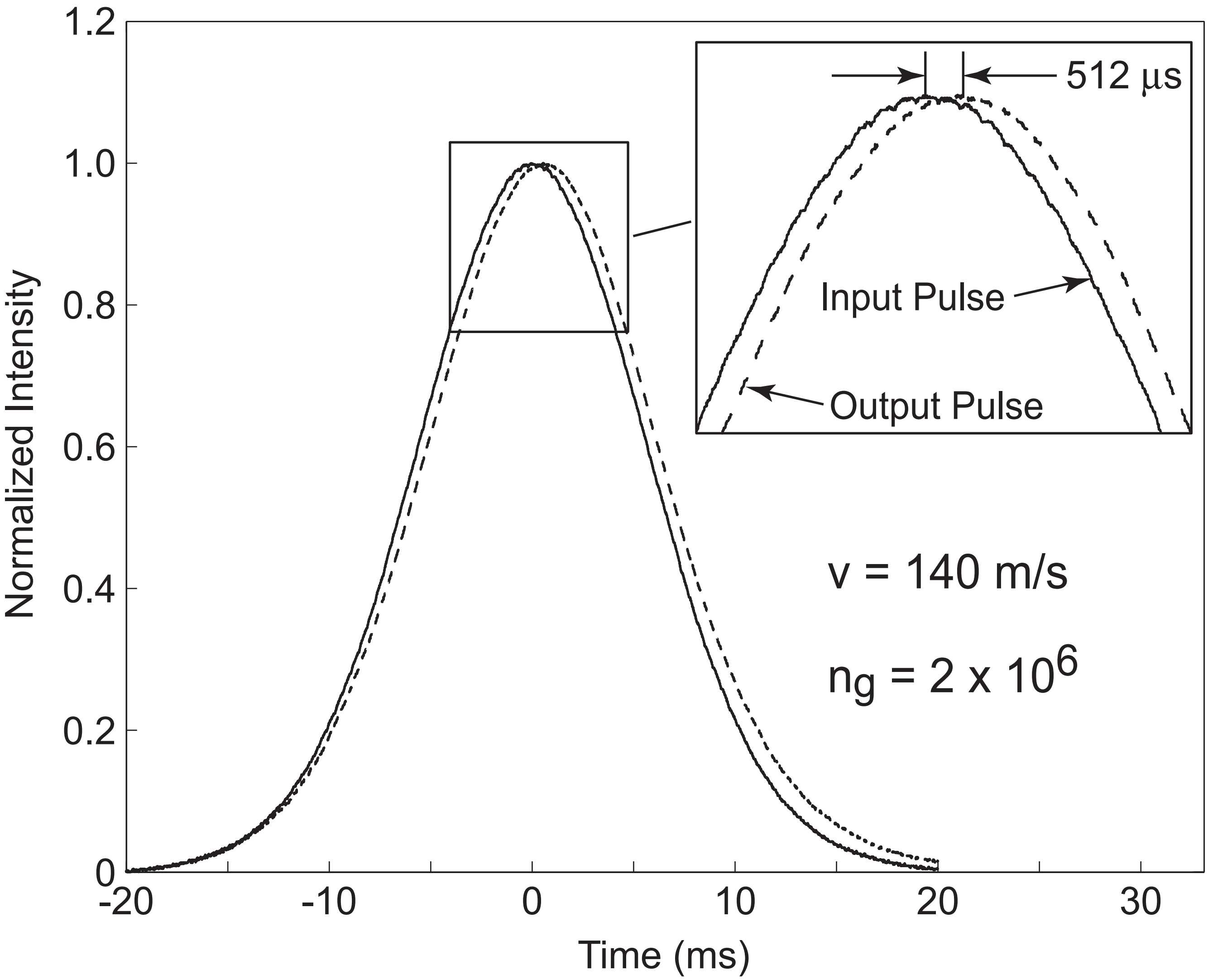
Fig. 3. Attenuation of the modulated component (probe beam) is plotted as a function of modulation frequency. The probe beam experiences decreased absorption at low modulation frequencies. The width of this hole is 37 Hz for low laser powers. The spectral hole is power broadened at high laser powers.

Experimental Setup Used to Observe SLow-Light in Ruby



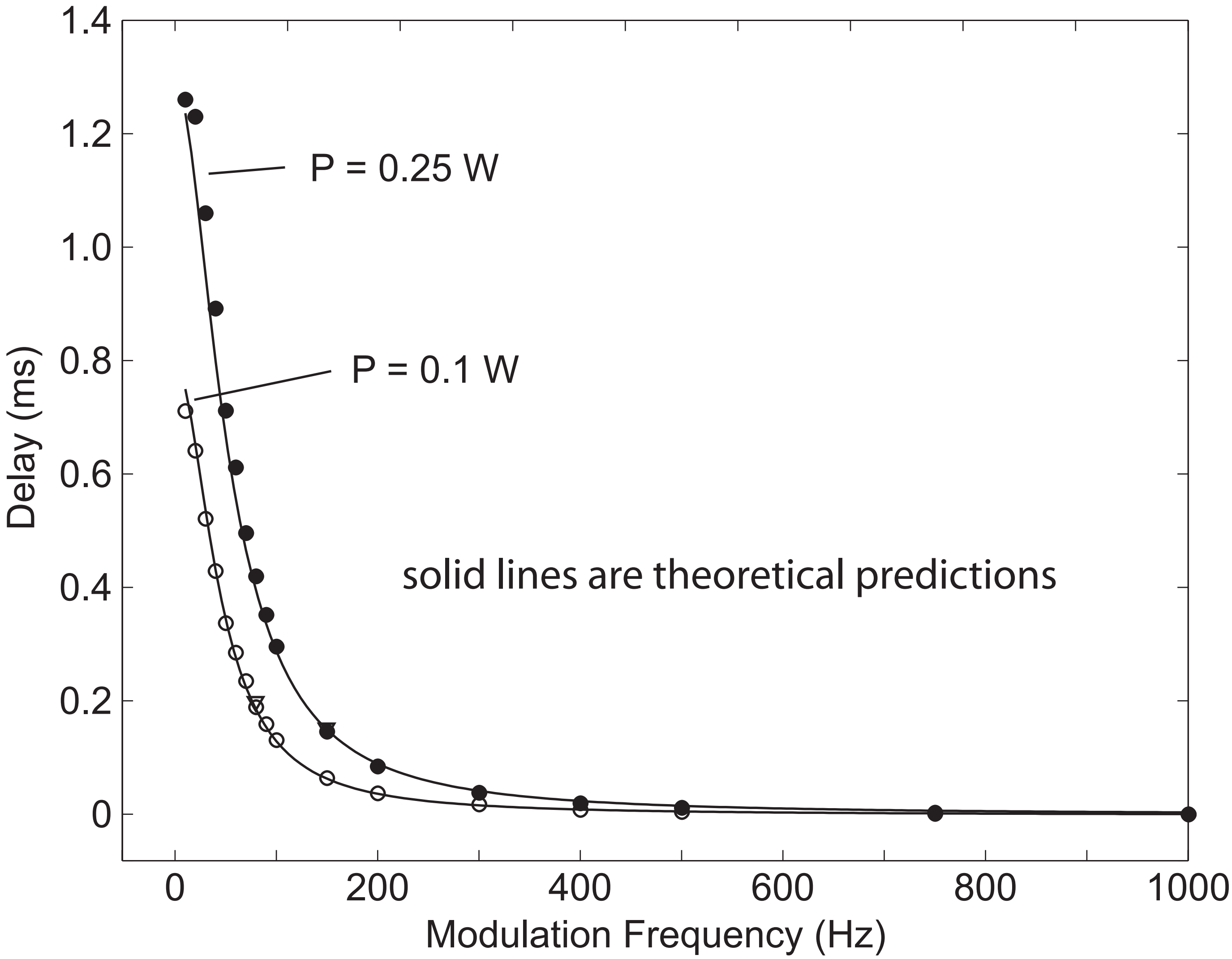
7.25 cm ruby laser rod (pink ruby)

Gaussian Pulse Propagation Through Ruby



No pulse distortion!

Measurement of Delay Time for Harmonic Modulation



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

“Slow” Light in Nanostructured Devices

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with

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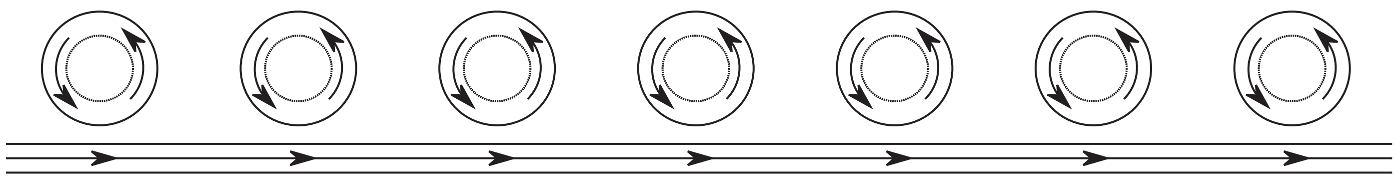
Nanofabrication

- Materials (artificial materials)
- Devices

(distinction?)

NLO of SCISSOR Devices

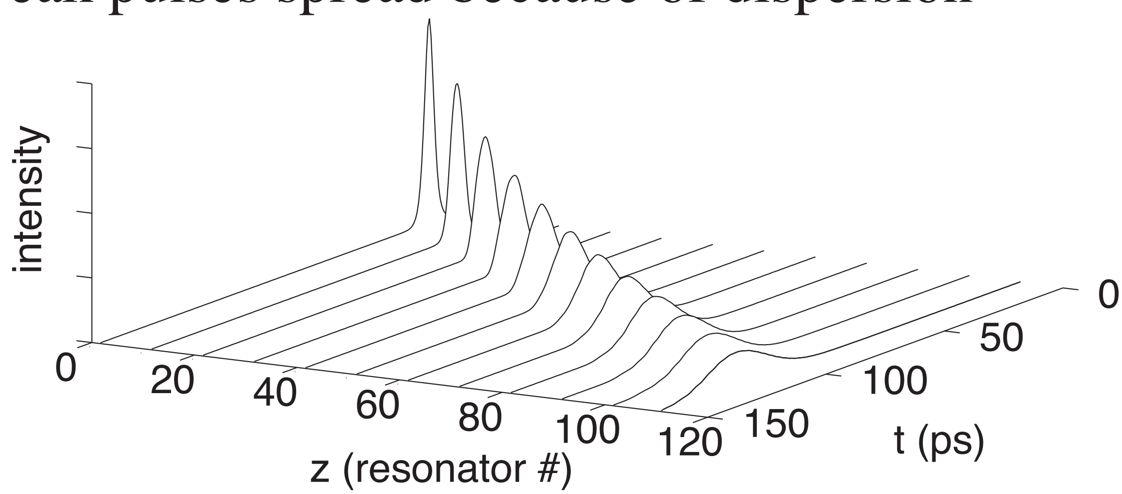
(Side-Coupled Integrated Spaced Sequence of Resonators)



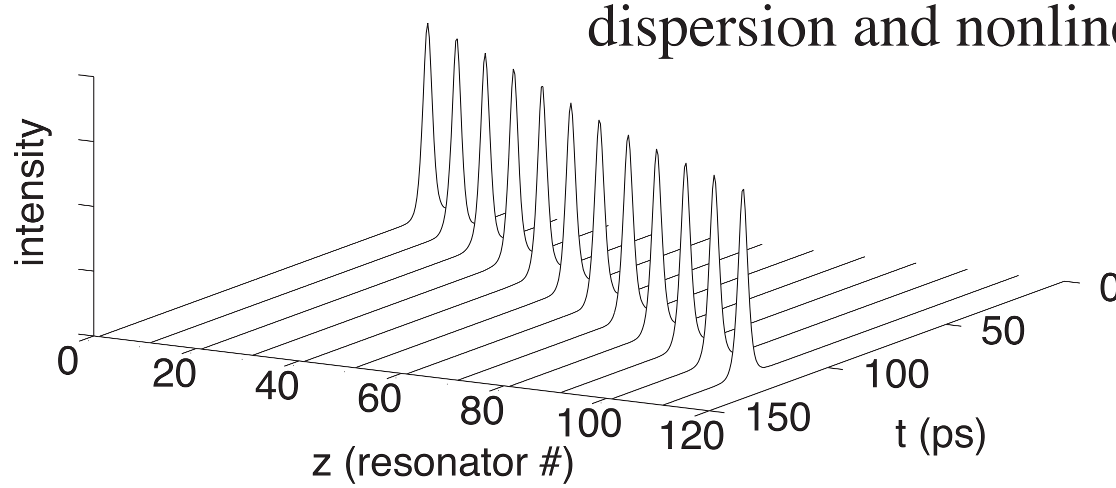
Shows slow-light, tailored dispersion, and enhanced nonlinearity

Optical solitons described by nonlinear Schrodinger equation

- Weak pulses spread because of dispersion

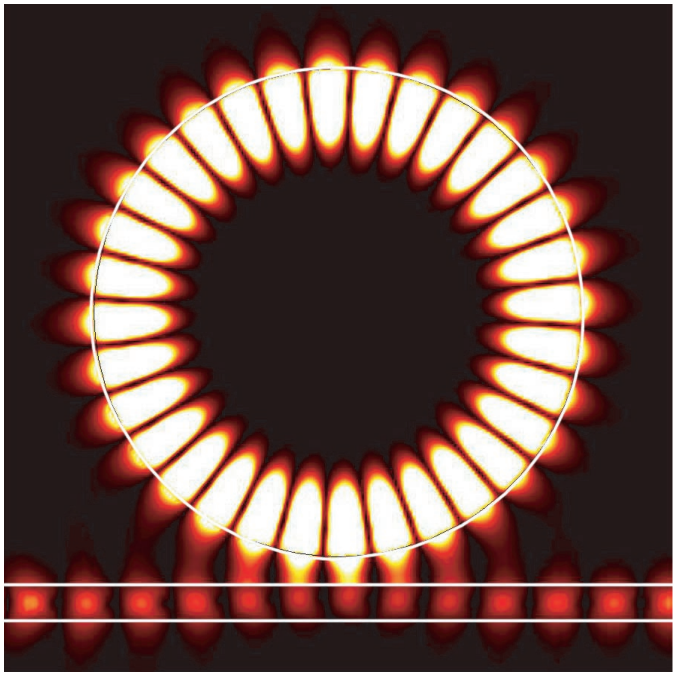


- But intense pulses form solitons through balance of dispersion and nonlinearity.

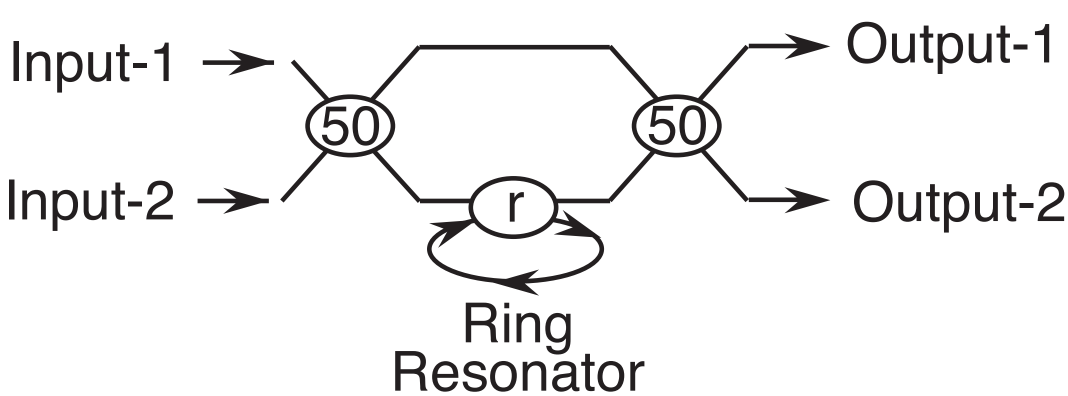


Ultrafast All-Optical Switch Based On Arsenic Triselenide Chalcogenide Glass

- 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)

A Real Whispering Gallery

St. Paul's Cathedral, London

Photonic Devices for Biosensing

Objective:

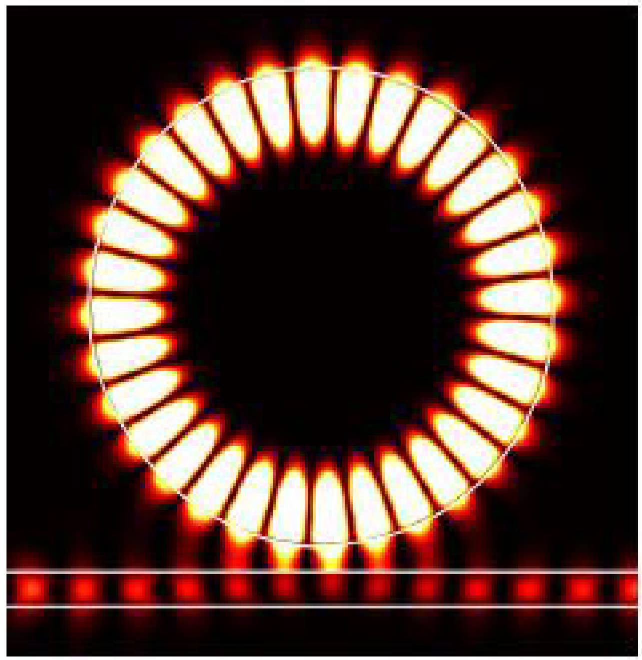
Obtain high sensitivity, high specificity detection of pathogens through optical resonance

Approach:

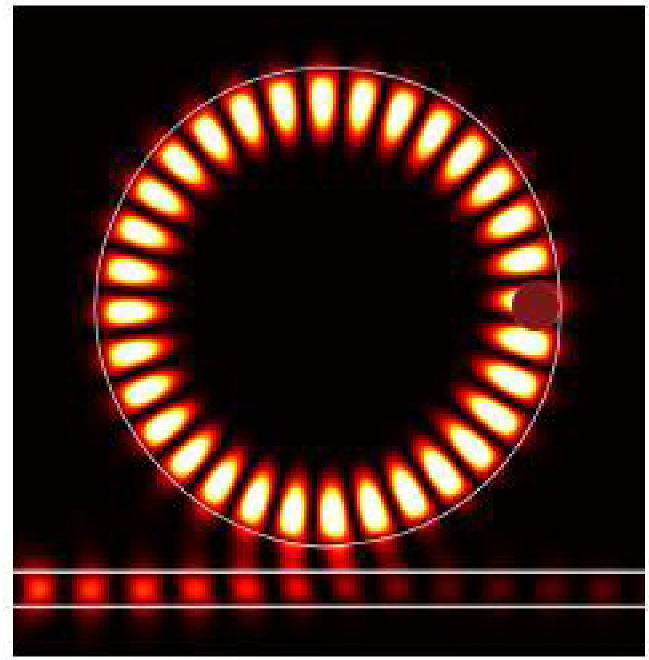
Utilize high-finesse whispering-gallery-mode disk resonator.

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.

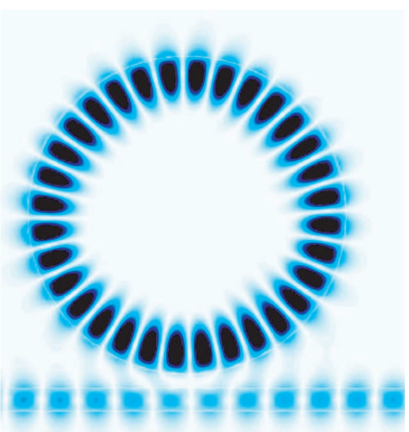
FDTD

Motivation

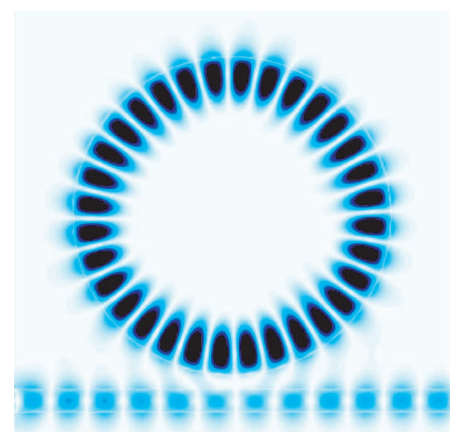
To exploit the ability of microresonators to enhance nonlinearities and induce strong dispersive effects for creating structured waveguides with exotic properties.

Currently, most of the work done in microresonators involves applications such as disk lasers, dispersion compensators and add-drop filters. There's not much nonlinear action!

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

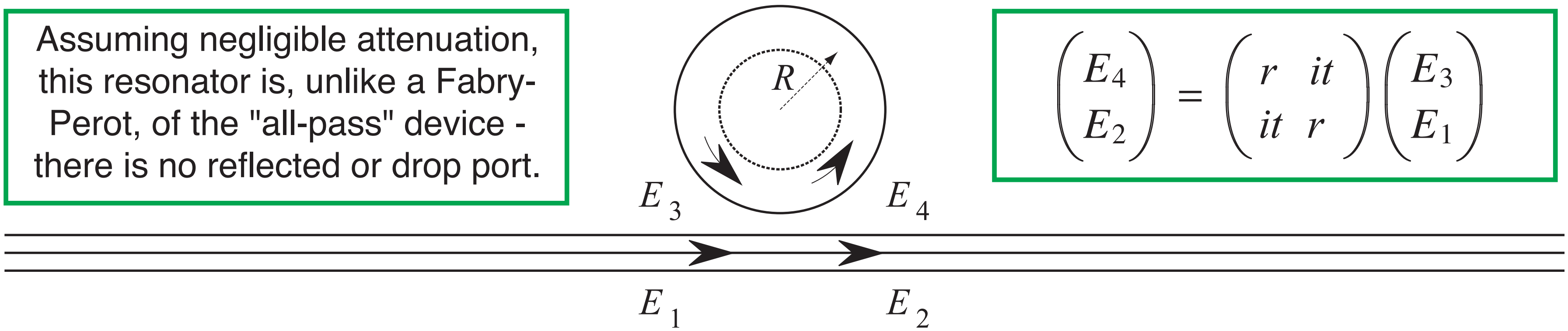


- slow light propagation
- induced dispersion
- enhanced nonlinearities



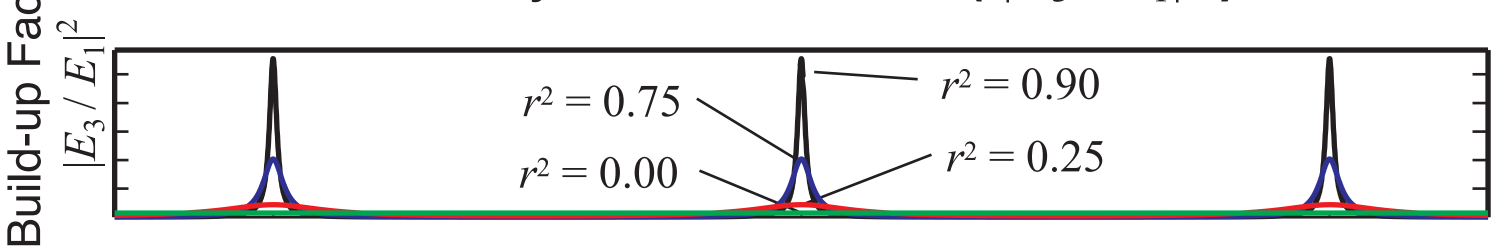
Properties of a Single Microresonator

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

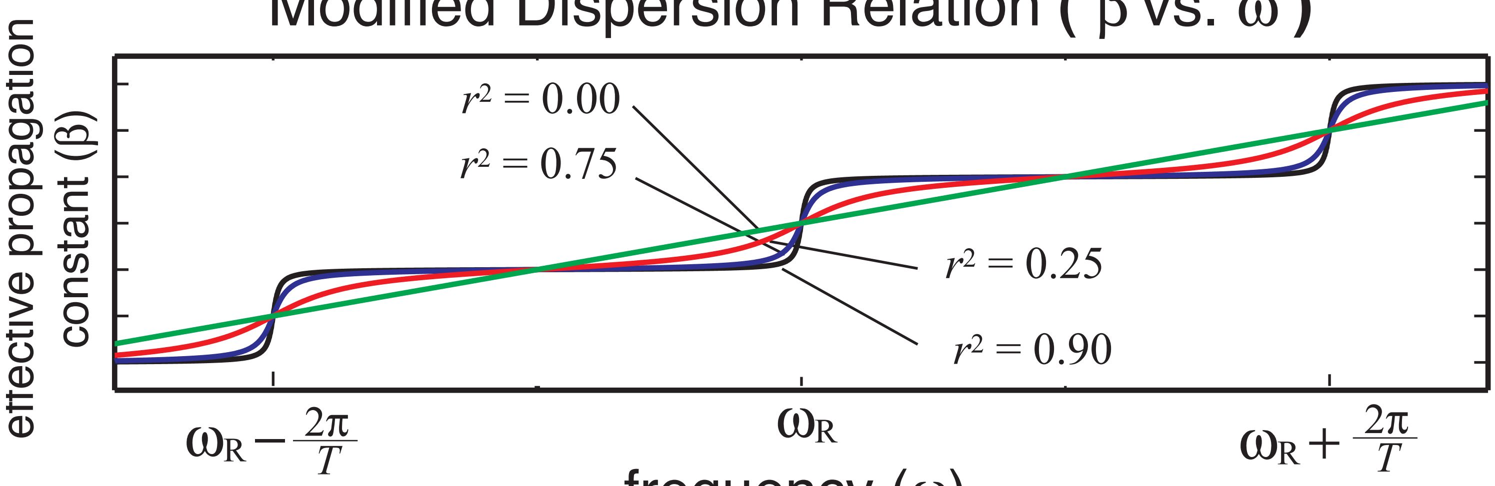


$$\begin{pmatrix} E_4 \\ E_2 \end{pmatrix} = \begin{pmatrix} r & it \\ it & r \end{pmatrix} \begin{pmatrix} E_3 \\ E_1 \end{pmatrix}$$

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



Modified Dispersion Relation (β vs. ω)



Definitions

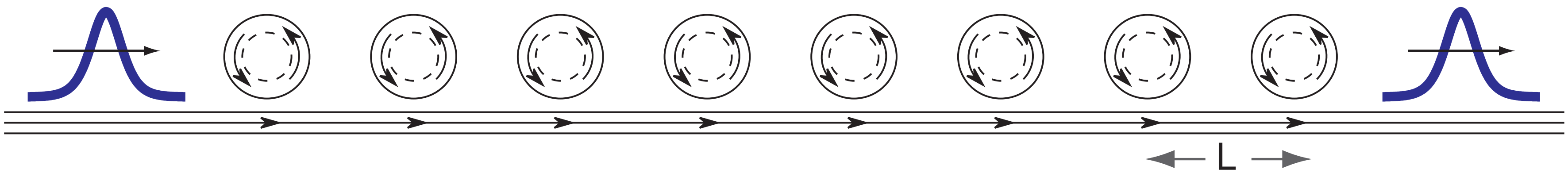
Finesse

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

Transit Time

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

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.

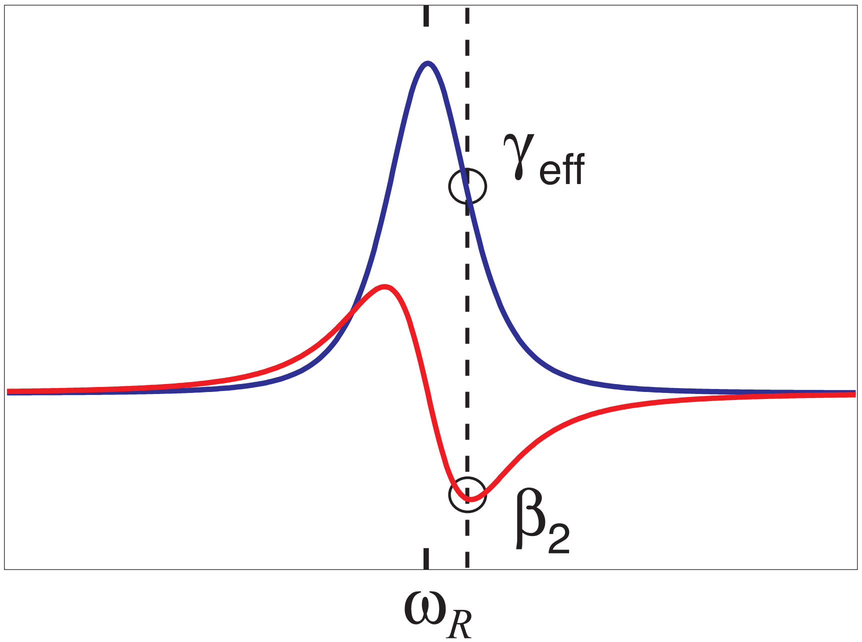
Nonlinear Schrödinger Equation (NLSE)

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

Fundamental Soliton Solution

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

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!

Soliton Propagation

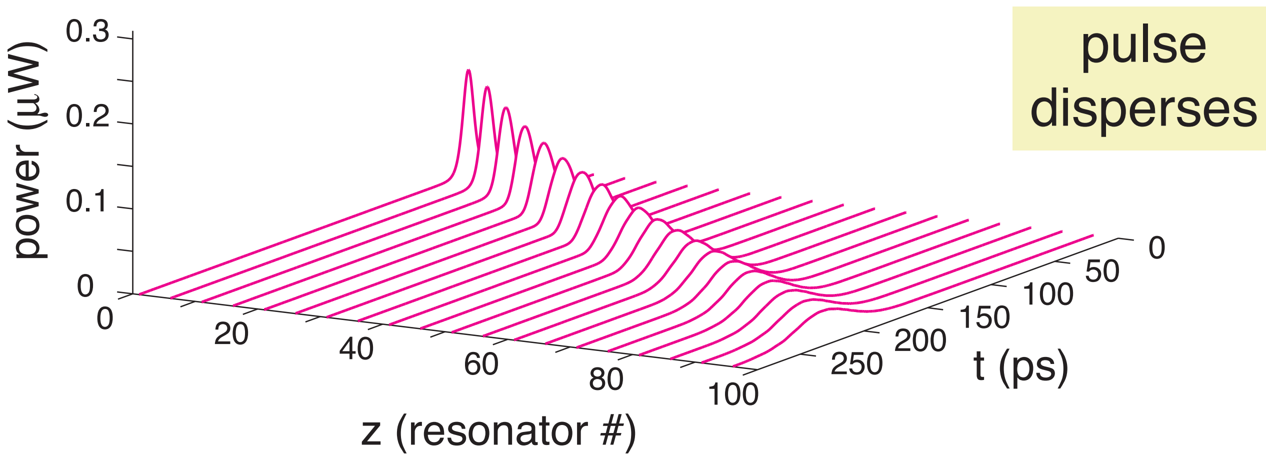
5 μm diameter resonators with a finesse of 30

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

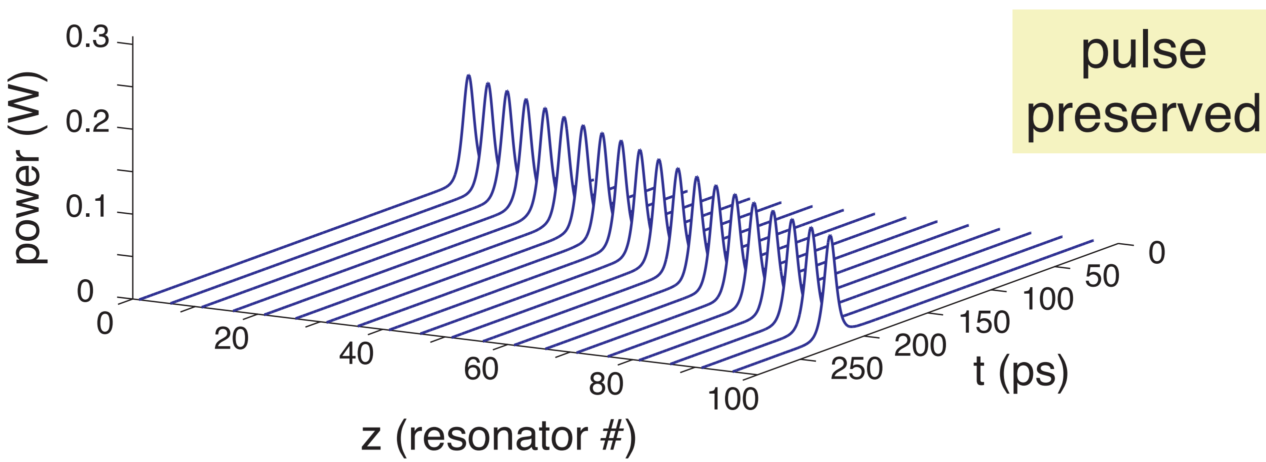
soliton may be excited via a 10 ps, 125mW pulse

simulation assumes a chalcogenide/GaAs-like nonlinearity

Weak Pulse

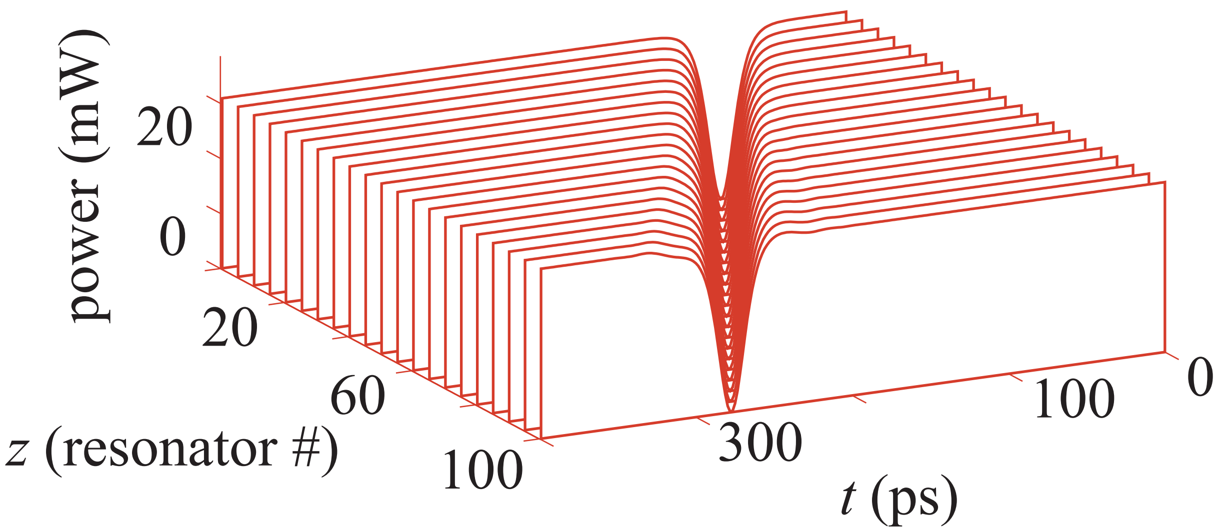


Fundamental Soliton



Dark Solitons

SCISSOR system also supports the propagation of dark solitons.



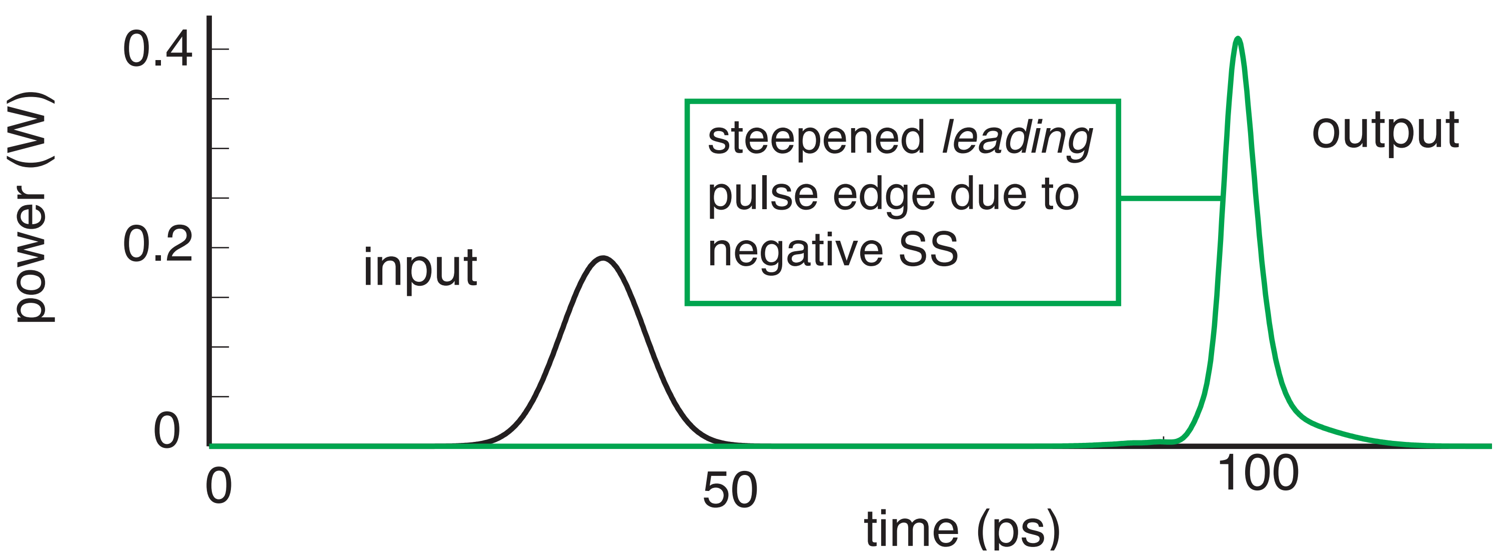
Higher-Order Effects - Self-Steepening

Higher order dispersive terms such as β_3 are present in the system and become more dominant as the pulsewidth becomes nearly as short as the cavity lifetime. Because the nonlinear enhancement is in fact frequency dependent, or (equivalently here) because the group velocity is intensity dependent, self-steepening of pulses is possible even for relatively long pulse widths.

A generalized NLSE:

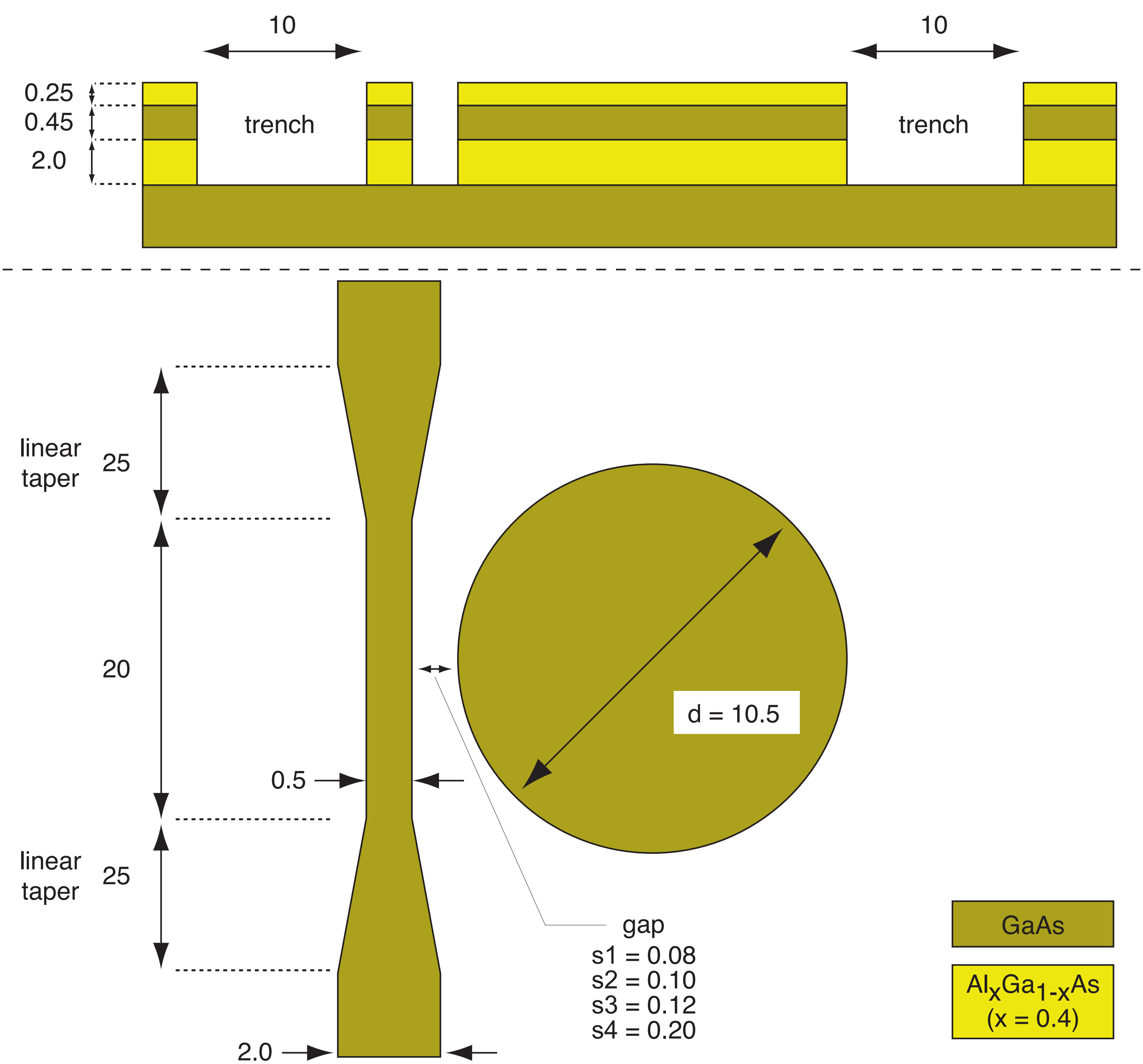
$$\frac{\partial}{\partial z}A = -i\frac{1}{2}\beta_2\frac{\partial^2}{\partial t^2}A - \frac{1}{6}\beta_3\frac{\partial^3}{\partial t^3}A + i\gamma|A|^2A - s\frac{\partial}{\partial t}|A|^2A$$

Self-steepening of a 20 ps Gaussian pulse after 100 resonators



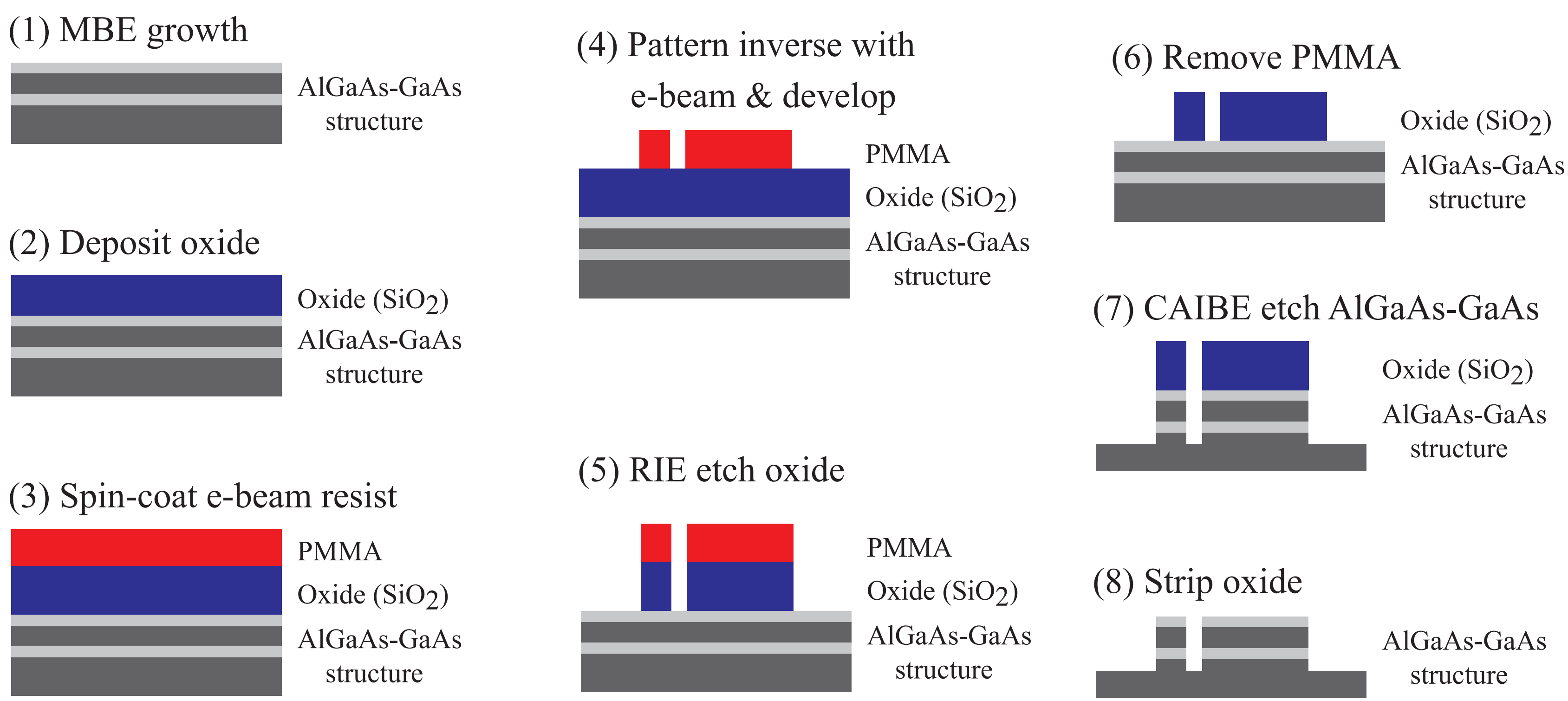
Microdisk Resonator Design

(Not drawn to scale)
All dimensions in microns



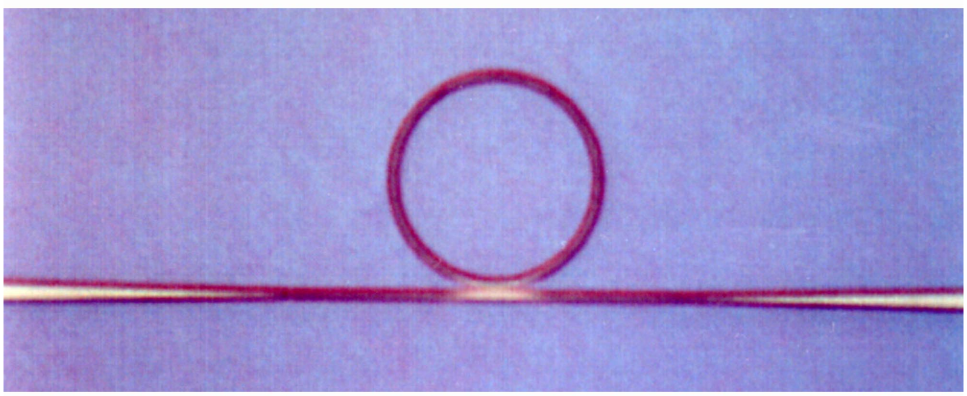
J. E. Heebner and R. W. Boyd

Photonic Device Fabrication Procedure



RWB - 10/4/01

Nonlinear Optical Loop-De-Loop



J.E. Heebner and R.W.B.

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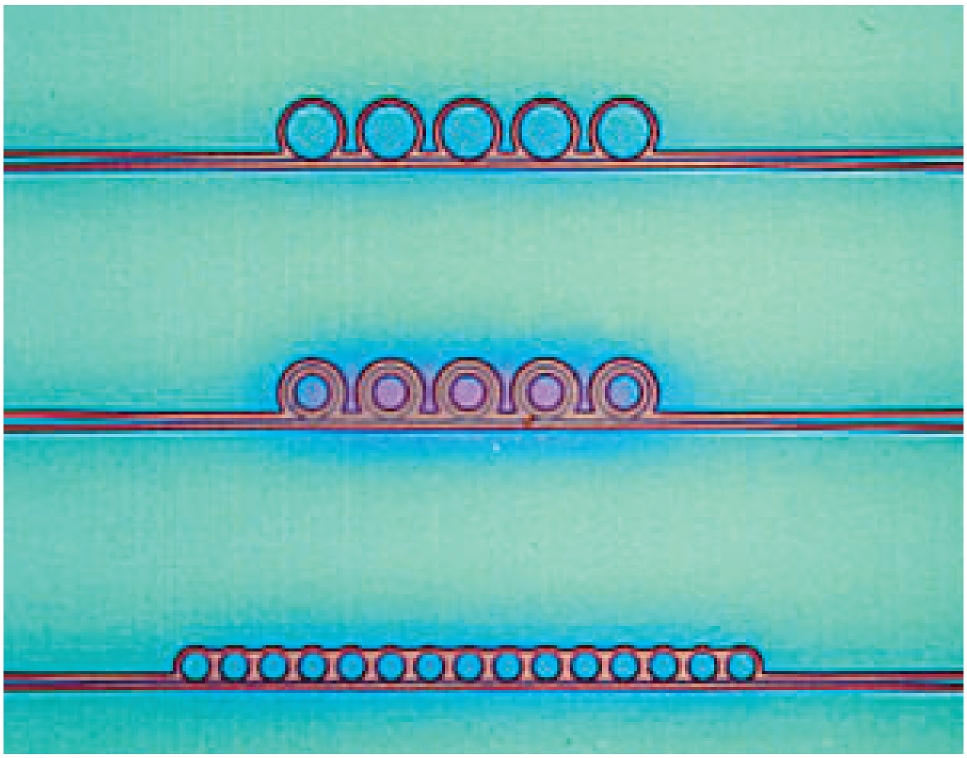

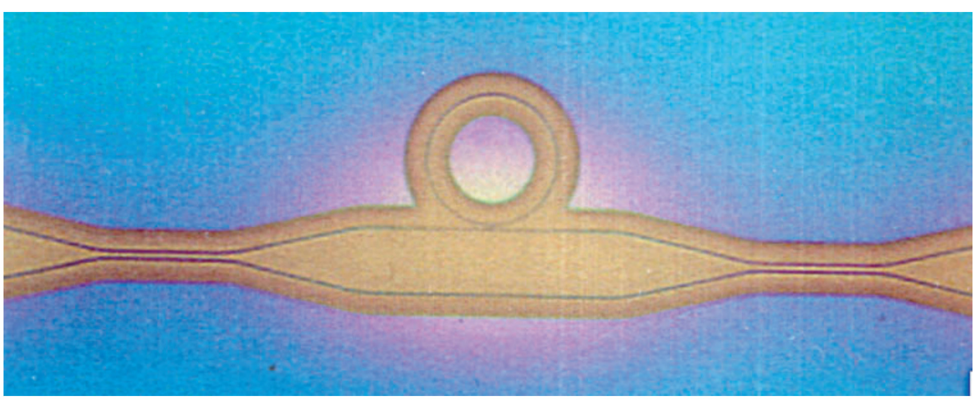

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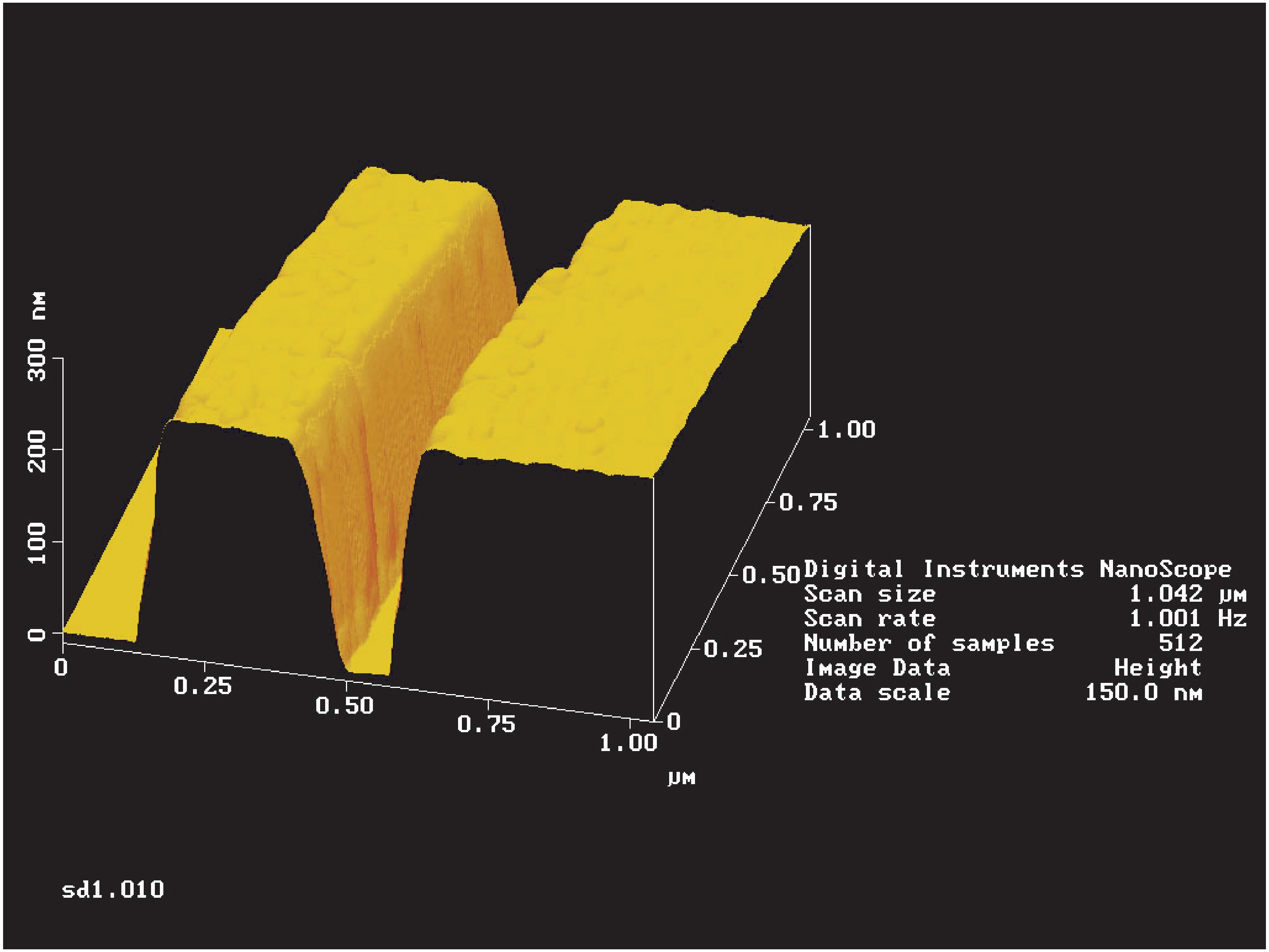
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Scan size 1.042 µм
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Photonic Devices in GaAs/AlGaAs