“Slow” Light in Nanostructured Devices

Robert W. Boyd

with

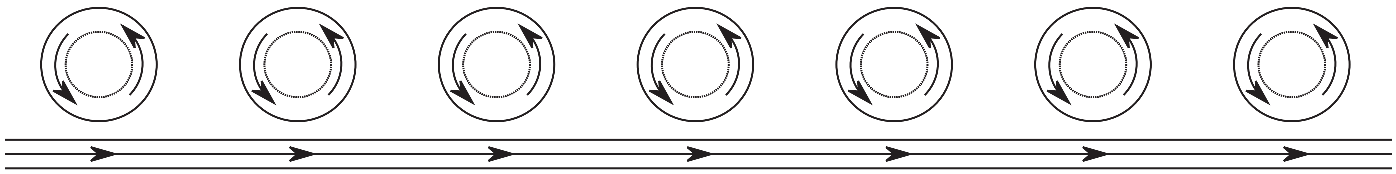
John Heebner, Nick Lepeshkin,
Aaron Schweinsberg, and Q-Han Park

The Institute of Optics, University of Rochester,
Rochester, NY 14627

Presented at PQE-2002

NLO of SCISSOR Devices

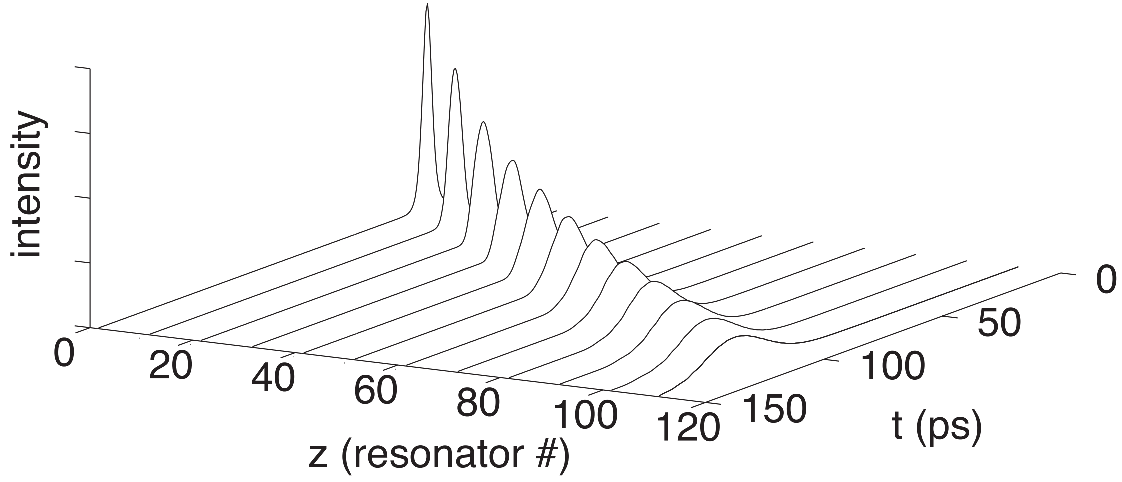
(Side-Coupled Integrated Spaced Sequence of Resonators)



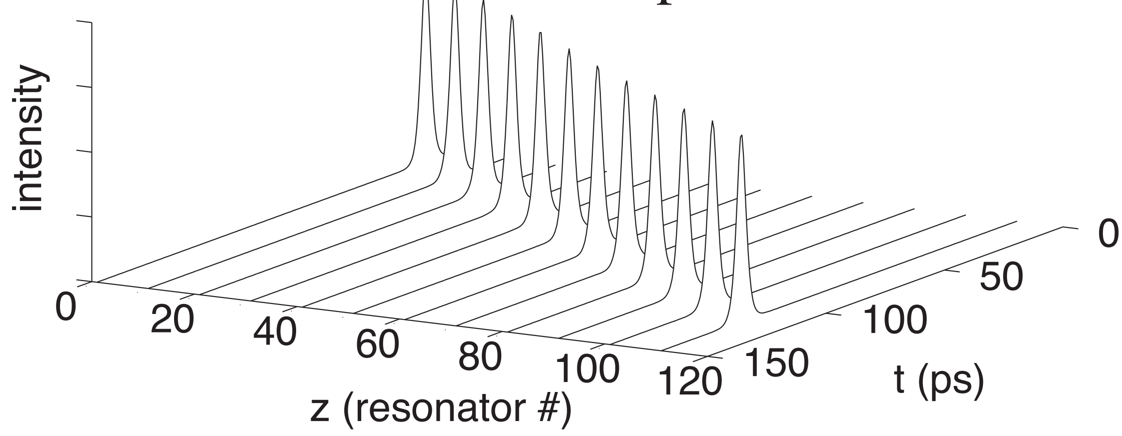
Shows slow-light, tailored dispersion, and enhanced nonlinearity

Optical solitons described by nonlinear Schrodinger equation

- Weak pulses spread because of dispersion

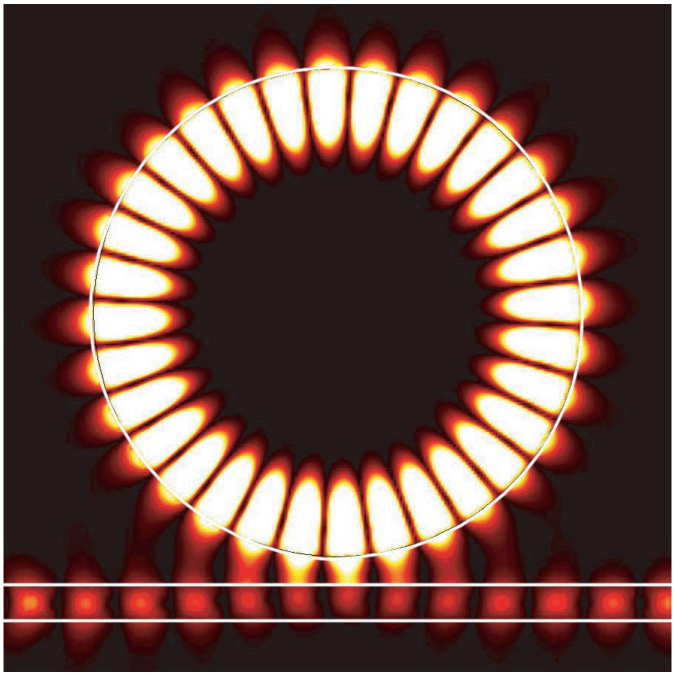


- But intense pulses form solitons through balance of dispersion and nonlinearity.

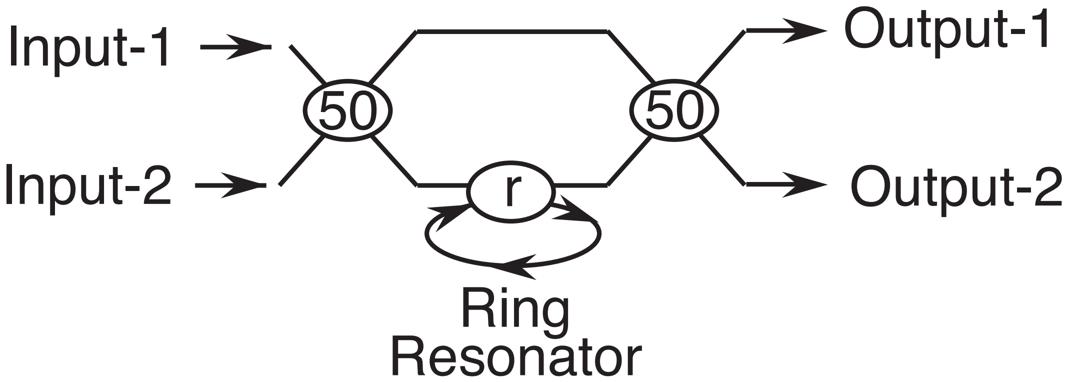


Ultrafast All-Optical Switch Based On Arsenic Triselenide Chalcogenide Glass

- 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 ≈ 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:

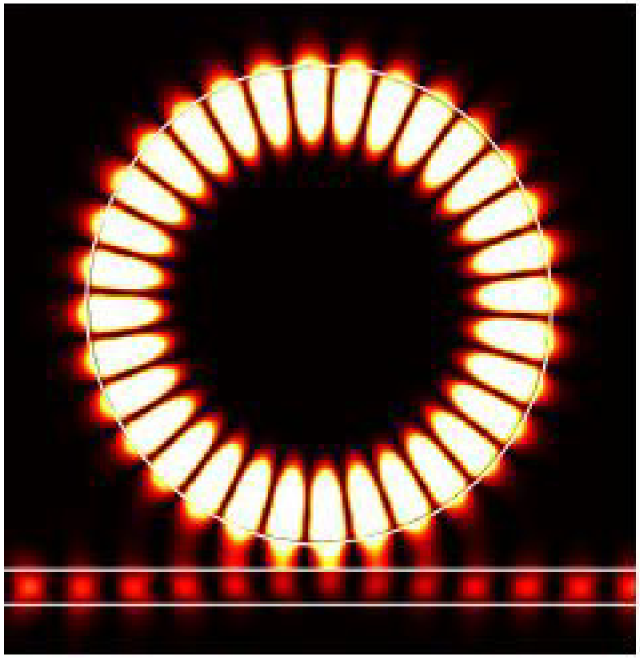
Obtain high sensitivity, high specificity detection of pathogens through optical resonance

Approach:

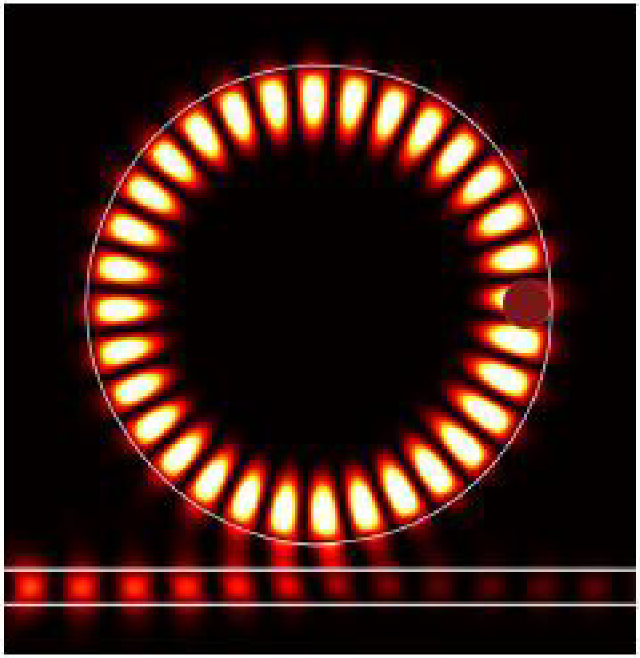
Utilize high-finesse whispering-gallery-mode disk resonator.

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

Simulation of device operation:



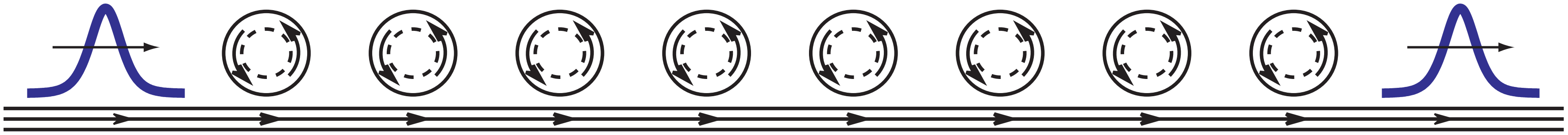
Intensity distribution in absense of absorber.



Intensity distribution in presence of absorber.

FDTD

Slow Light, Induced Dispersion, Enhanced Nonlinearity, Self-Steepening, and Optical Solitons in a Side-Coupled Integrated Spaced Sequence Of Resonators



SCISSOR

John E. Heebner
Q-Han Park
Robert W. Boyd

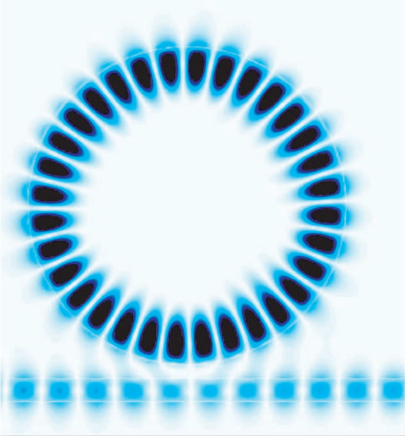
The Institute of Optics
Nonlinear Optics
University of Rochester

Motivation

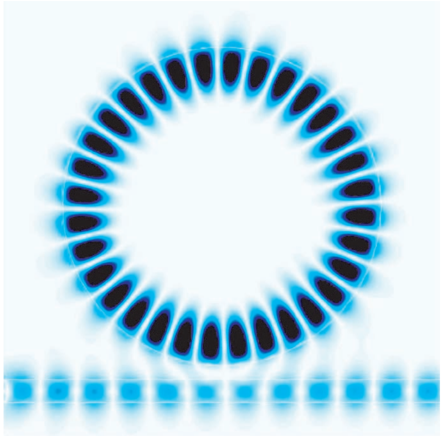
To exploit the ability of microresonators to enhance nonlinearities and induce strong dispersive effects for creating structured waveguides with exotic properties.

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:

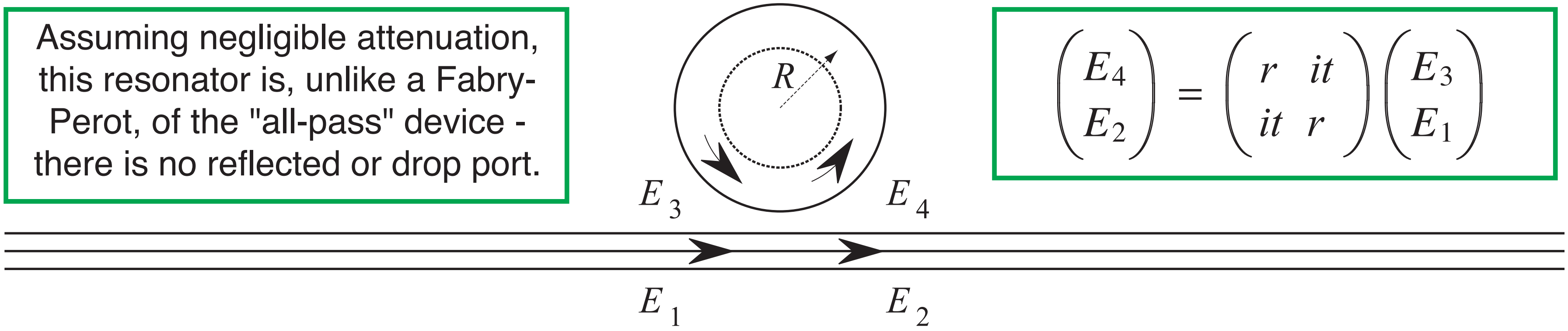


- slow light propagation
- induced dispersion
- enhanced nonlinearities



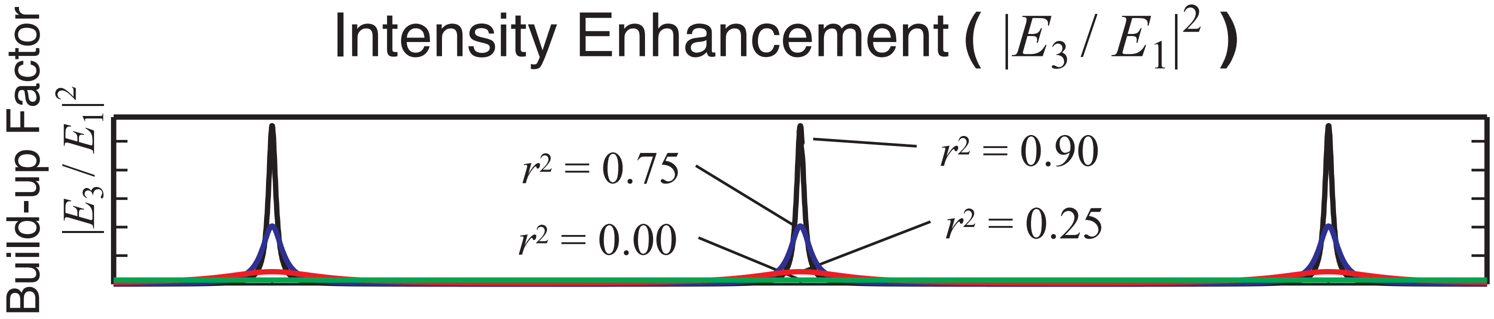
Properties of a Single Microresonator

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

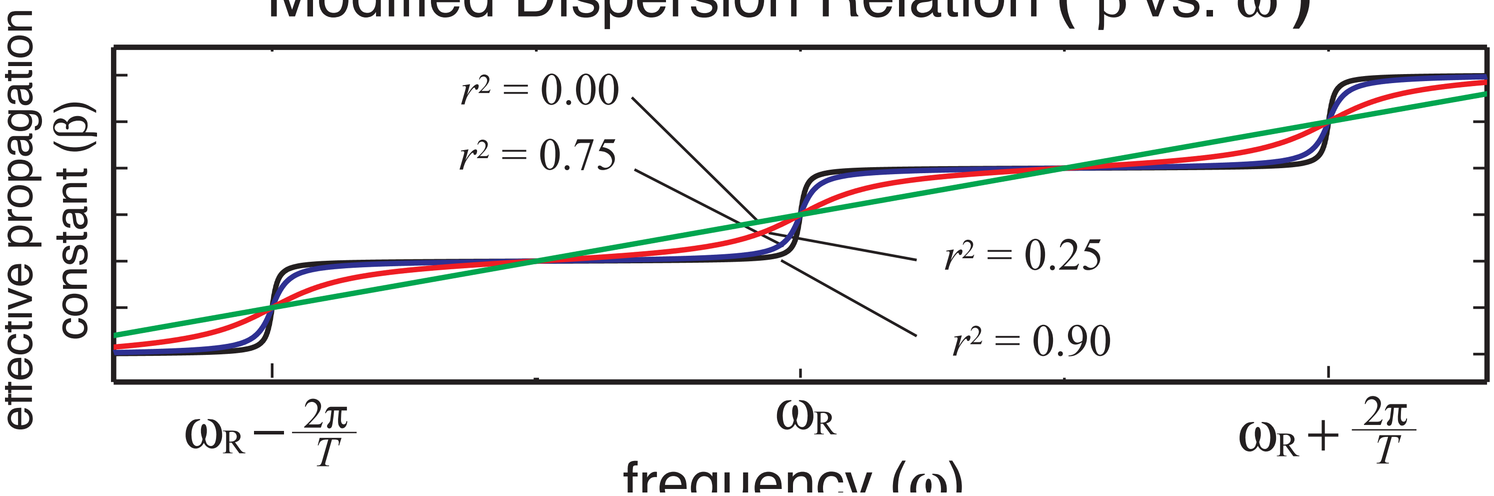


$$\begin{pmatrix} E_4 \\ E_2 \end{pmatrix} = \begin{pmatrix} r & it \\ it & r \end{pmatrix} \begin{pmatrix} E_3 \\ E_1 \end{pmatrix}$$

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



Modified Dispersion Relation (β vs. ω)



Definitions

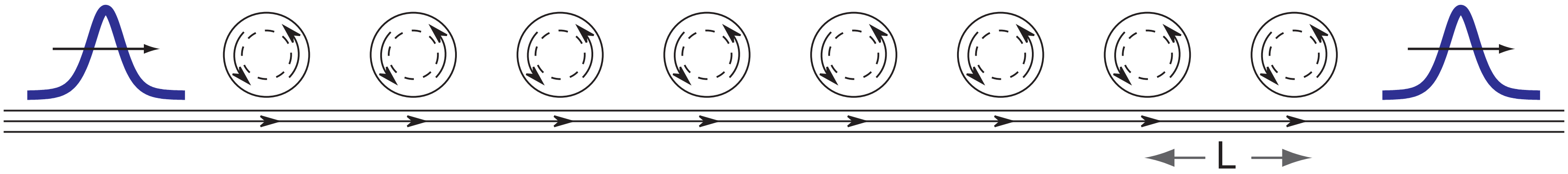
Finesse

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

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.

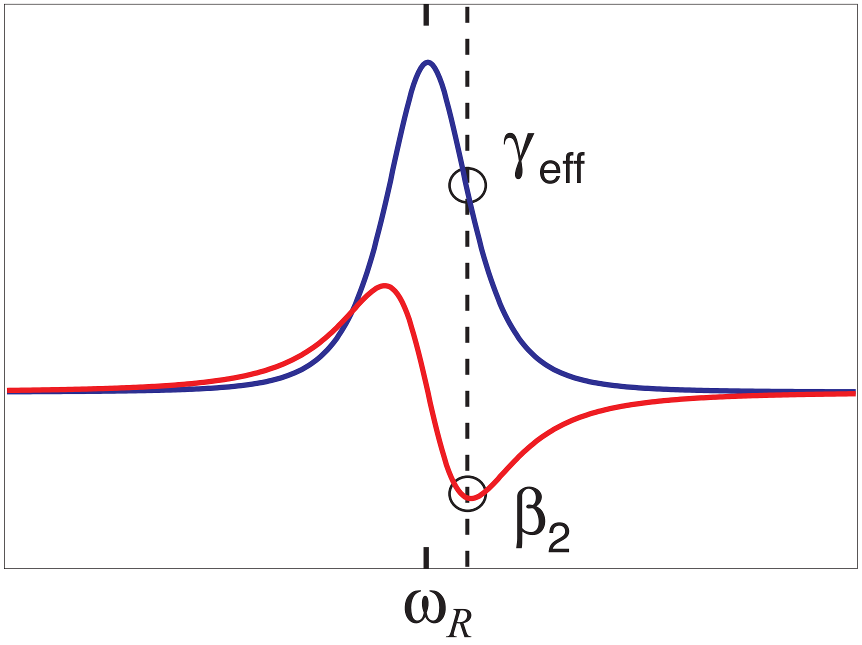
Nonlinear Schrödinger Equation (NLSE)

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

Fundamental Soliton Solution

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

Balancing Dispersion & Nonlinearity



soliton amplitude

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

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

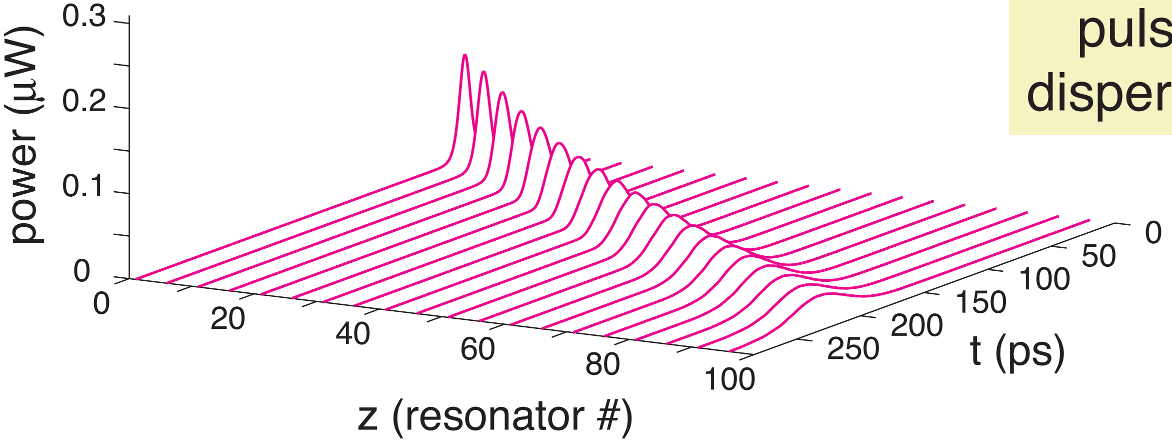
5 μm diameter resonators with a finesse of 30

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

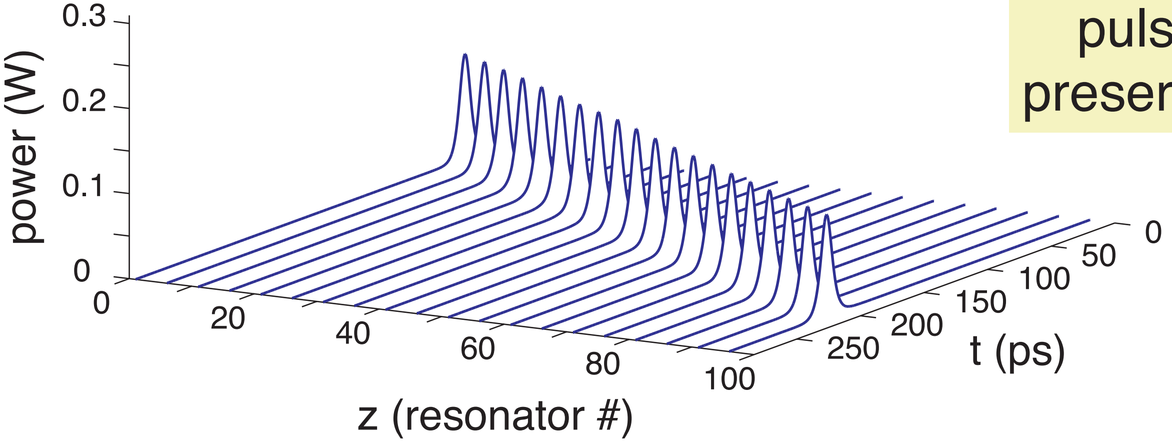
simulation assumes a chalcogenide/GaAs-like nonlinearity

Weak Pulse



pulse disperses

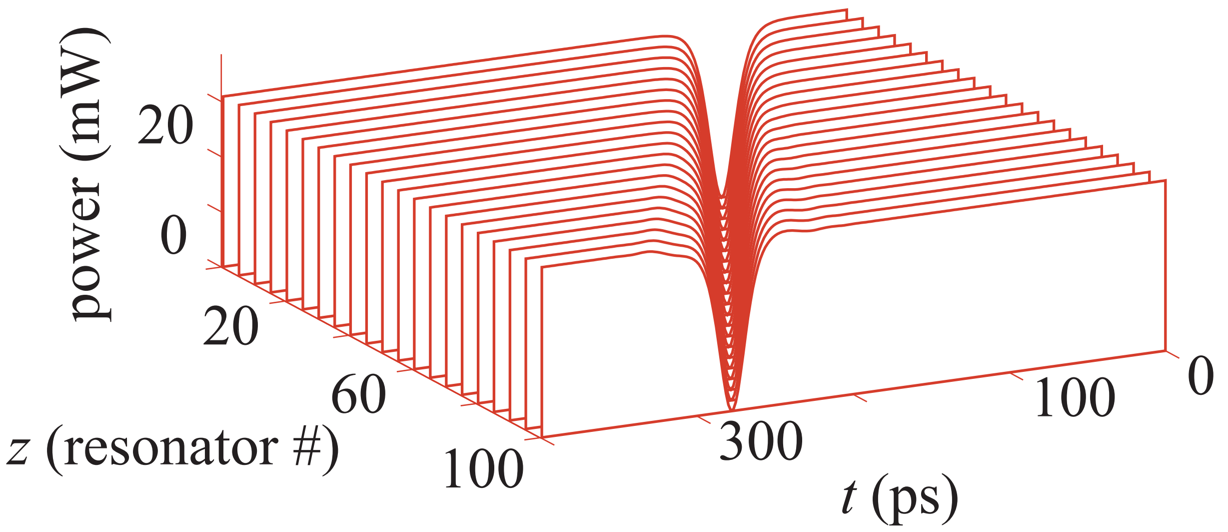
Fundamental Soliton



pulse preserved

Dark Solitons

SCISSOR system also supports the propagation of dark solitons.



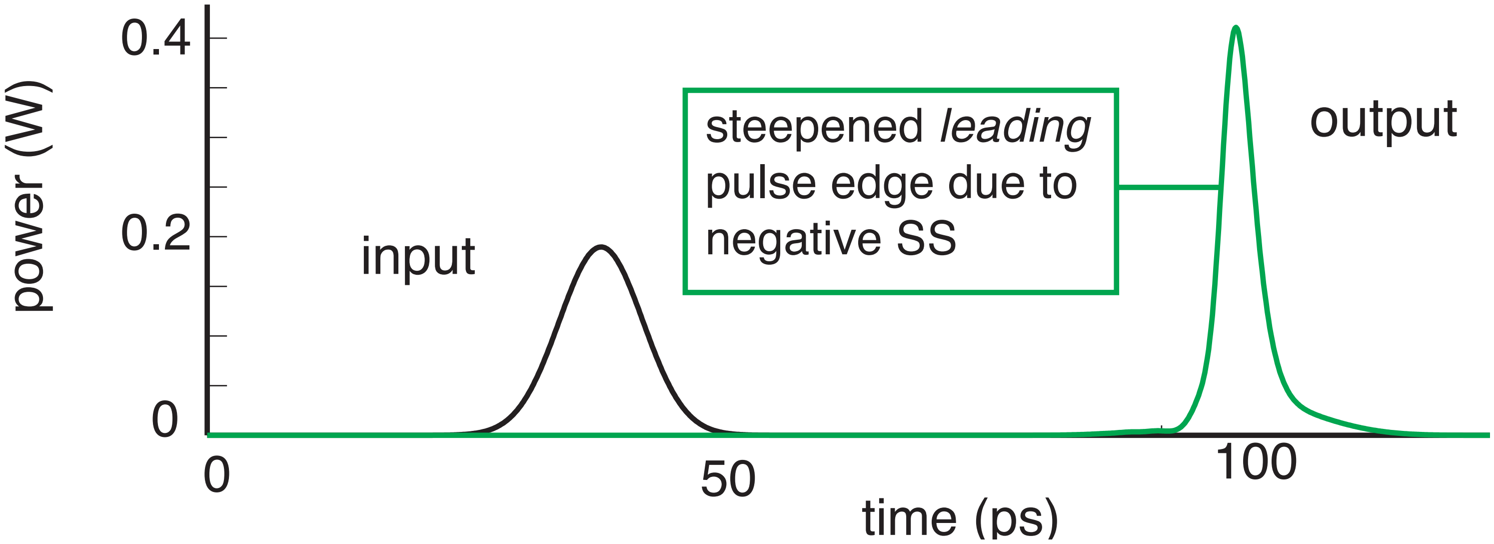
Higher-Order Effects - Self-Steepening

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



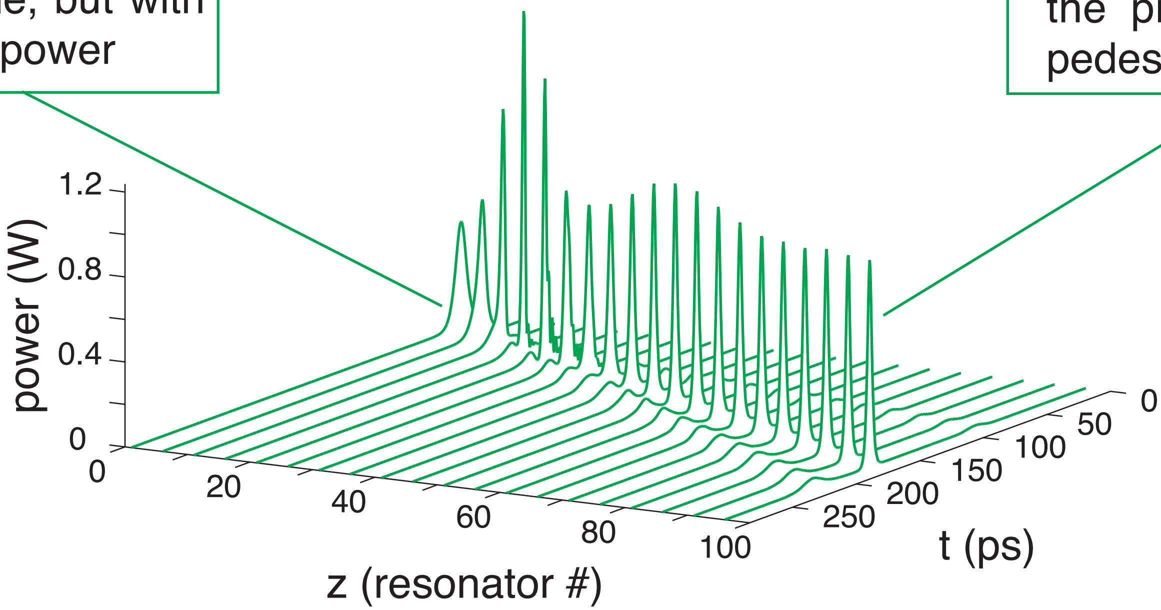
Soliton Splitting and Compression

The dispersive nature of the nonlinear enhancement (self-steepening) leads to an intensity-dependent group velocity which splits an N-order soliton into N fundamental solitons of differing peak intensities and widths.

Here, a 2^{nd} - order "breathing" soliton splits into 2 fundamental solitons:

Same parameters as used for the previous soliton example, but with 4X the launch power

Note that one pulse is compressed and is uncorrupted by the presence of a pedestal.



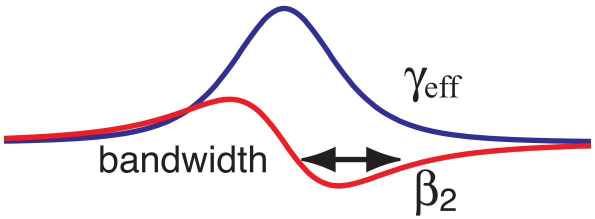
Limitations

Bandwidth

A 5 μm diamater disk with a finesse of 200 possesses a bandwidth of 100 GHz

Cascading N resonators further decreases the available bandwidth;

fortunately the scaling is governed by β_4 effects which results in a reduction of $N^{1/4}$



Manufacturability

Tolerances on resonator diameter and gap spacing to be met within 200 nm

variance in gap spacing analogous to hyperfine distribution

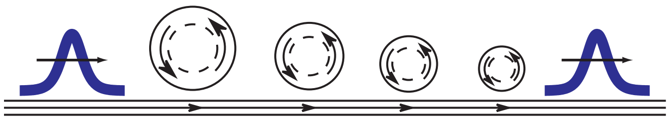
variance in radius/index analogous to Doppler broadening

Attenuation - dominated by scattering losses

may be counterbalanced by:

1) gain

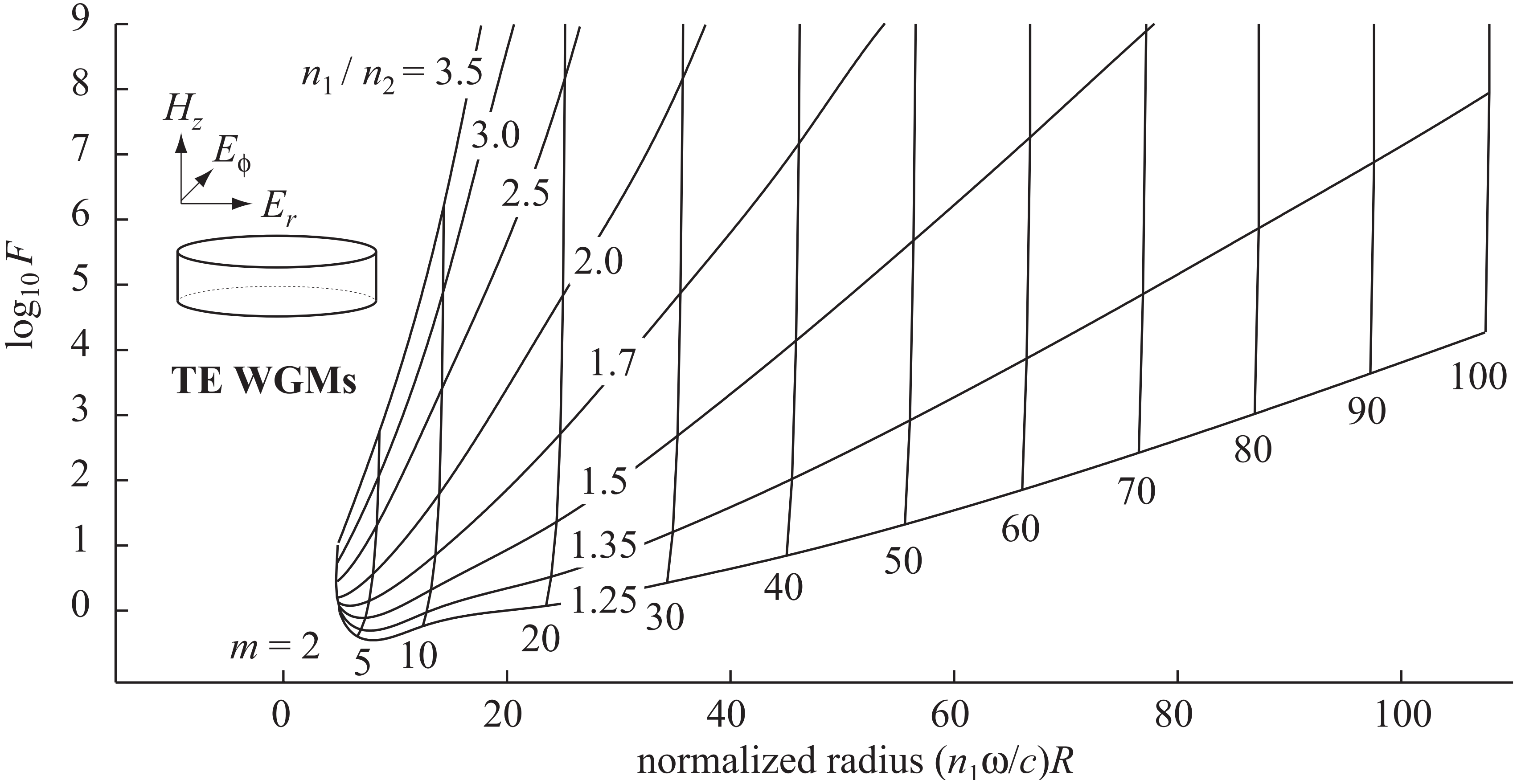
2) dispersion decreasing SCISSOR :



Radiation Losses

Is it really possible to confine light within a wavelength-size structure?

- Radiation losses provide fundamental limit to the finesse of a WGM resonator.
- Radiation losses are analogous to fiber bending losses.
- But these losses can be rendered negligible through use of a large dielectric contrast.



Conclusions

The SCISSOR exhibits strong dispersive & nonlinear properties and supports solitons. It incorporates the essence of photonic bandgap (PBG) enhancement found in structures such as CROWs & Bragg gratings *without the gap itself*.

Manufacturability will require some ingenuity, but already resonators are already in use as all-pass filters and tunable dispersion

SCISSORs have the potential for producing soliton propagation effects at the integrated photonics scale. The possibilities for structurally engineered waveguides of this type include:

- Pulse compression / imaging in an integrated device
- Optical Time Division Multiplexing (OTDM)
- Soliton-based optical switching (perhaps w/ a few photons)
- Slow-light propagation (group-matched acousto-optics)
- EO,TO - Tunable NLSE propagation (A theorist's dream)
- Just about any other generalized NLSE effect

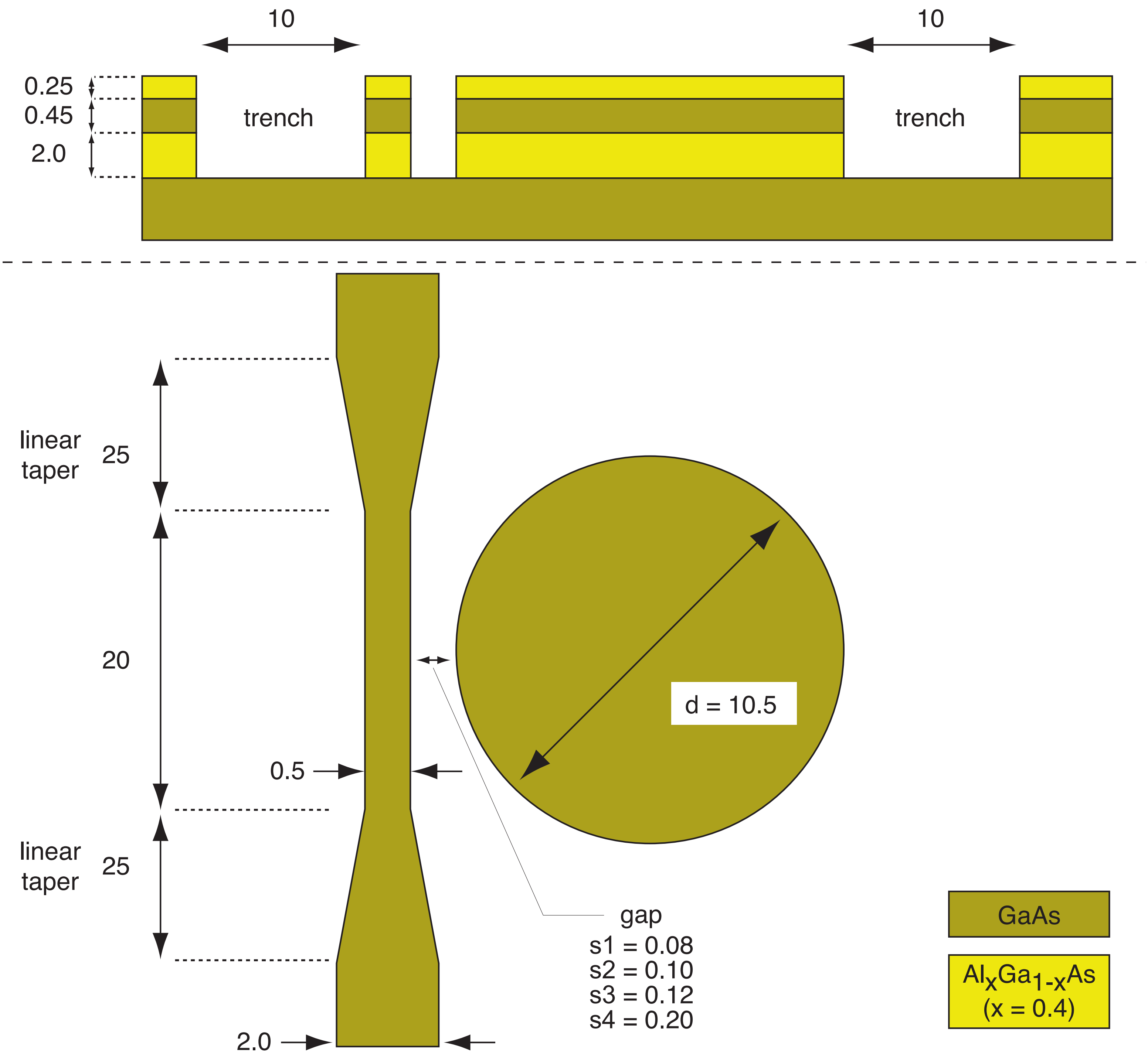
Nanofabrication

- Materials (artificial materials)
- Devices

(distinction?)

Microdisk Resonator Design

(Not drawn to scale)
All dimensions in microns



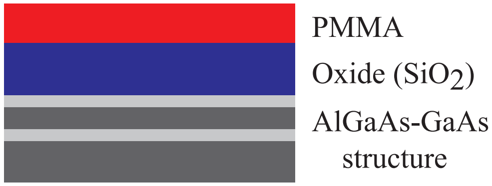
J. E. Heebner and R. W. Boyd

Photonic Device Fabrication Procedure

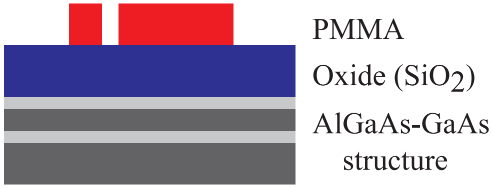
(1) MBE growth

(2) Deposit oxide

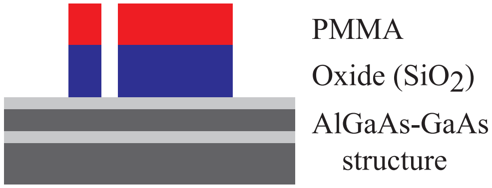
(3) Spin-coat e-beam resist



(4) Pattern inverse with e-beam & develop



(5) RIE etch oxide



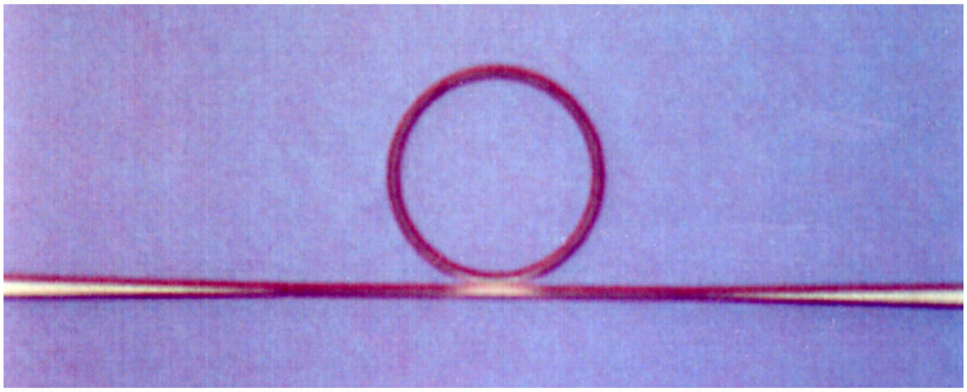
(6) Remove PMMA

(7) CAIBE etch AlGaAs-GaAs

(8) Strip oxide

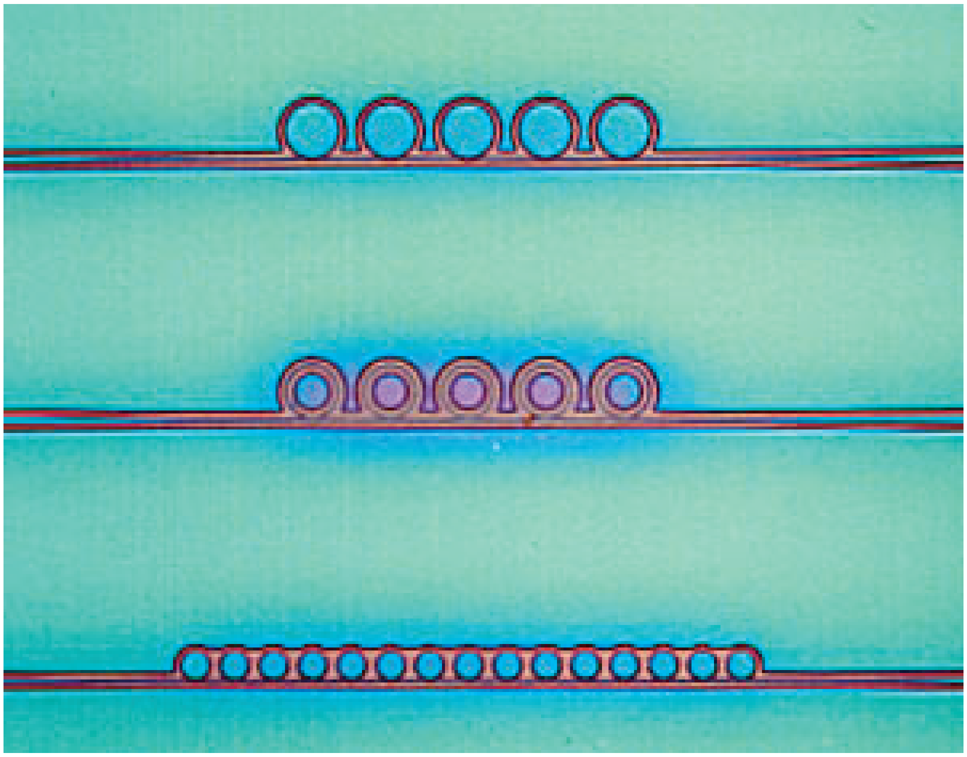
RWB - 10/4/01

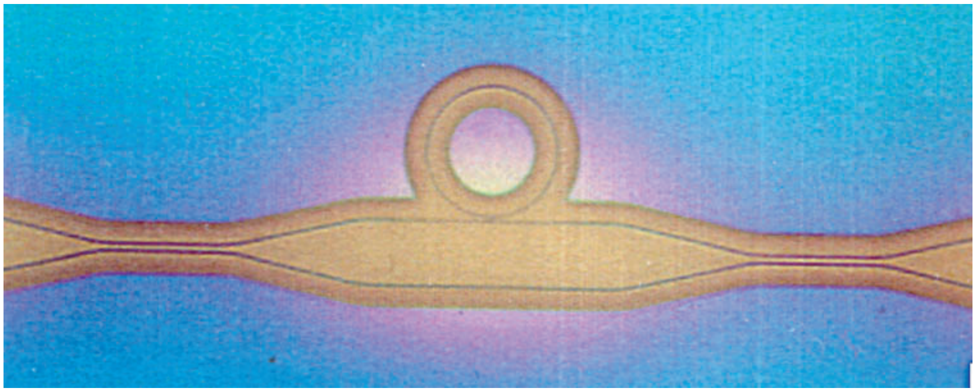
Nonlinear Optical Loop-De-Loop



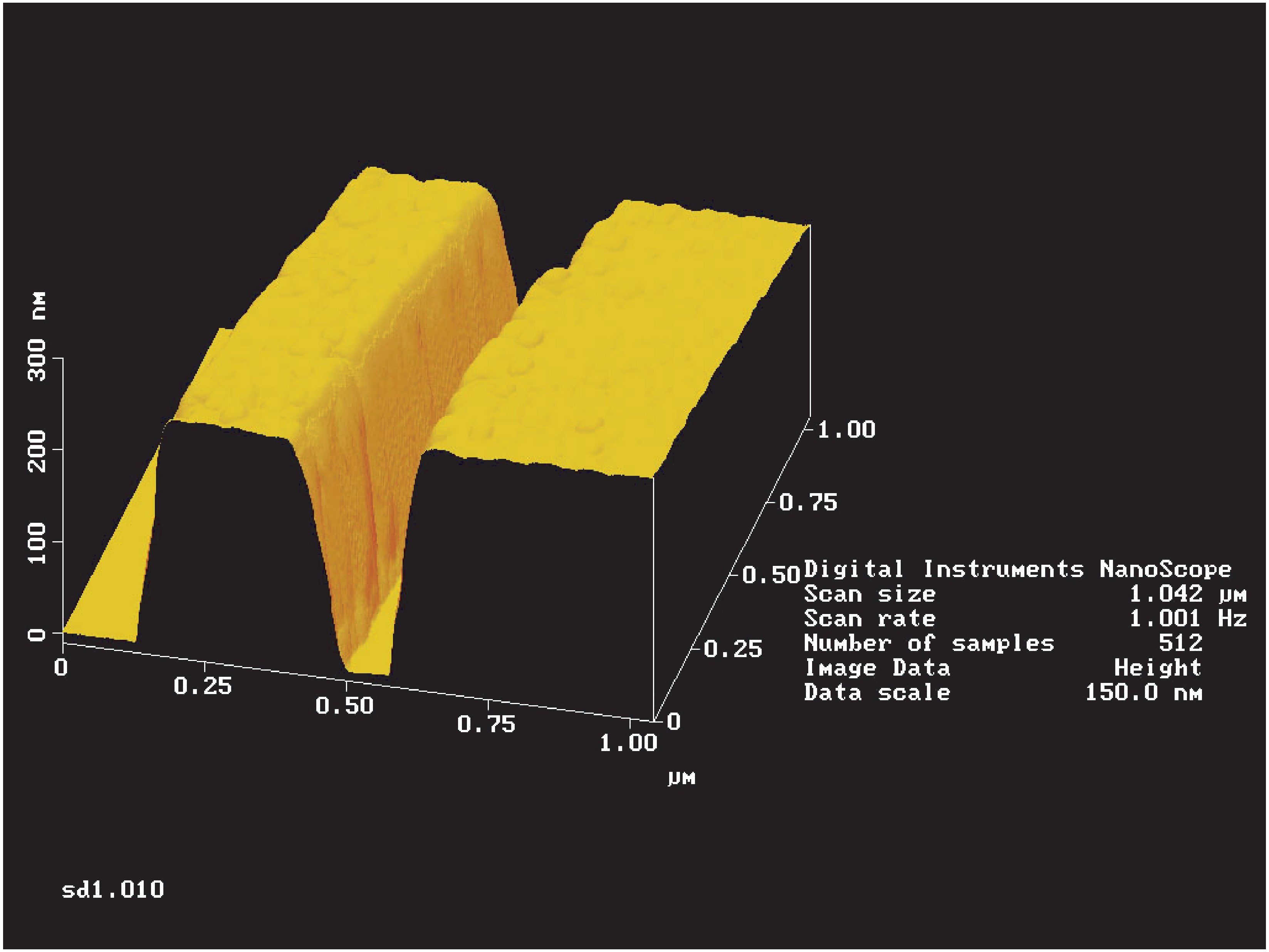
J.E. Heebner and R.W.B.

r





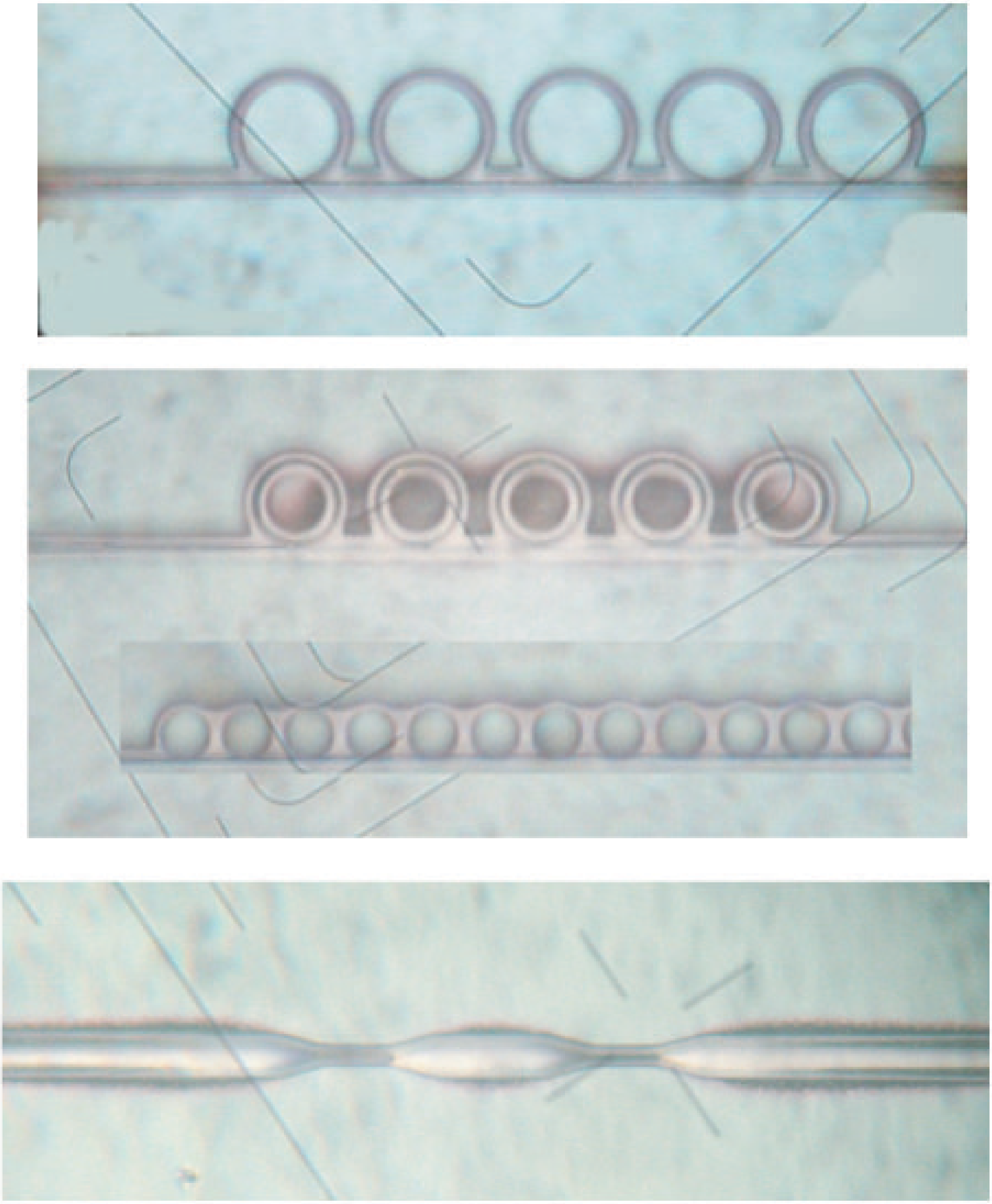
e i s



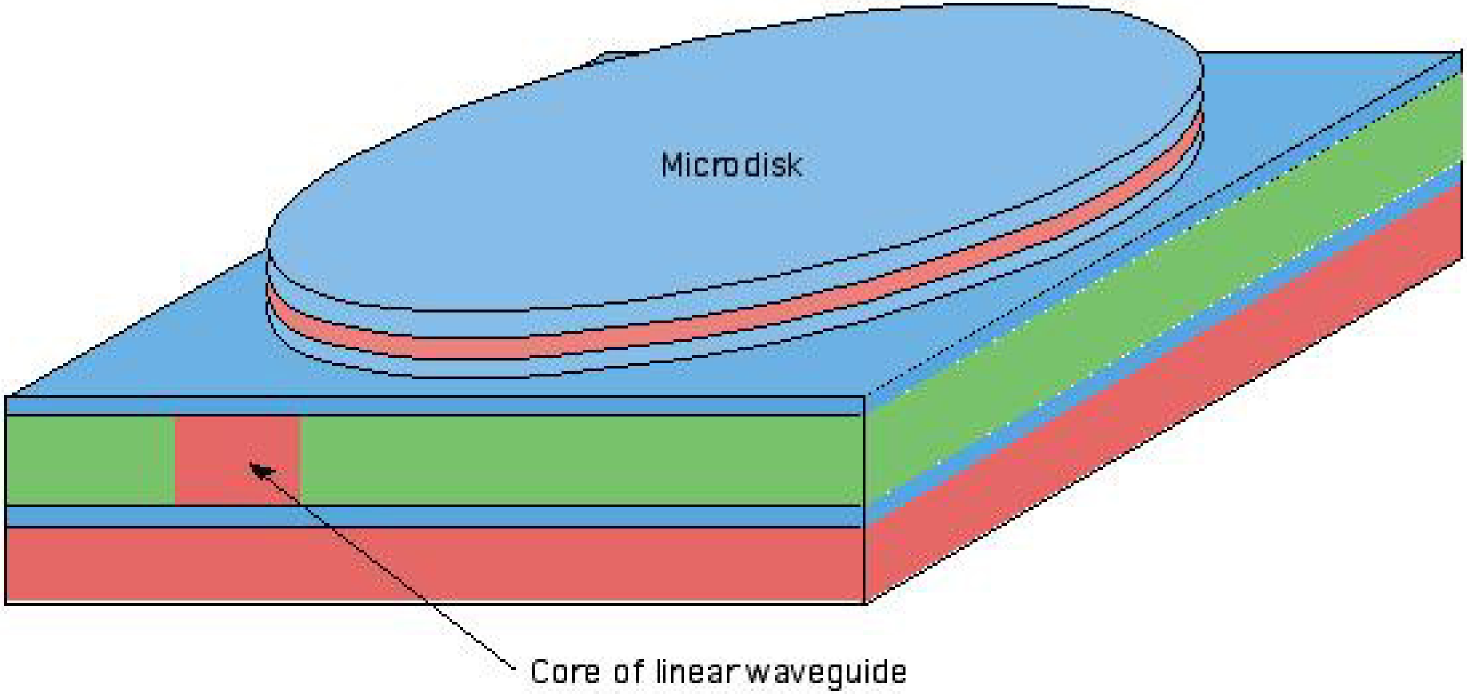
Digital Instruments NanoScope
Scan size 1.042 µM
Scan rate 1.001 Hz
Number of samples 512
Image Data Height
Data scale 150.0 nM

a

Photonic Devices in GaAs/AlGaAs



Microdisk Resonator Design / Vertically Coupled Structure



🟥 High refractive index (GaAs or AlGaAs superlattice)

🟩 Medium refractive index (intermixed superlattice)

🟦 Low refractive index (AlGaAs)

GWW - 10/8/01