Perspectives on Nonlinear Optics

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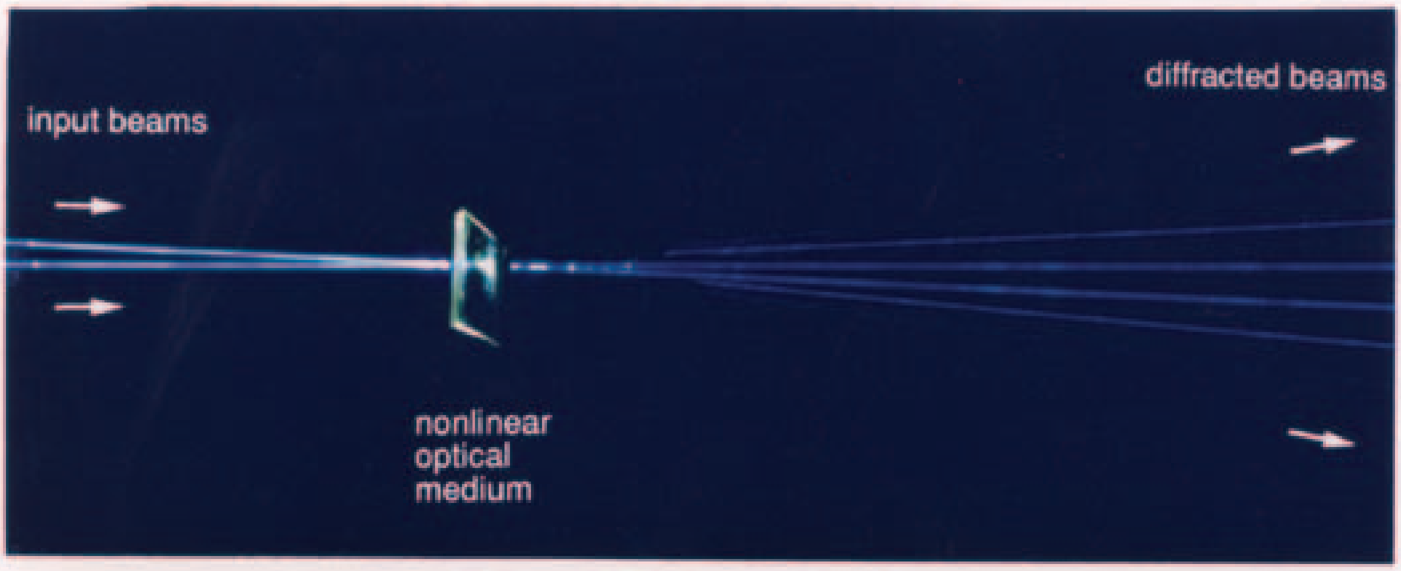
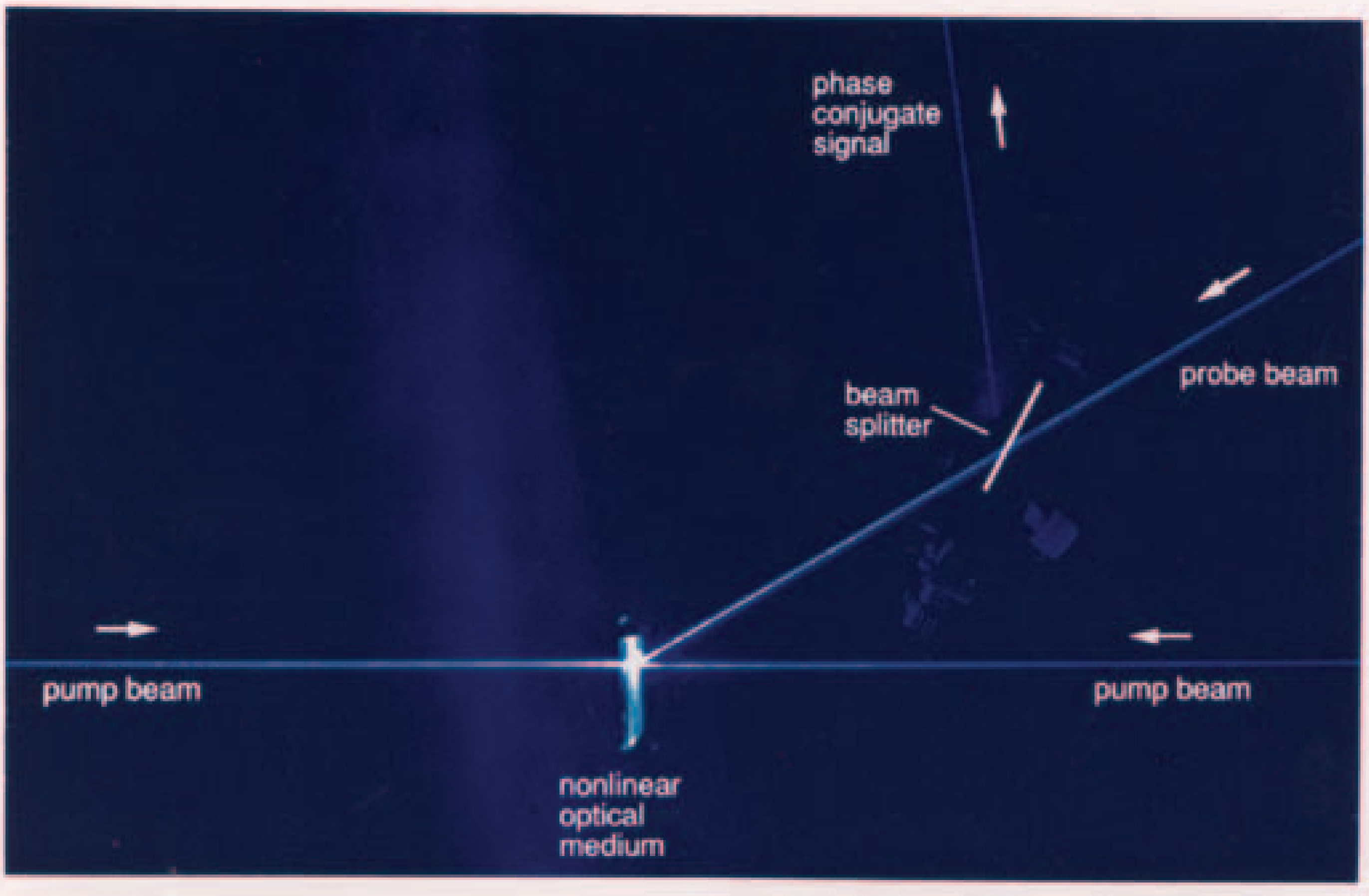
Presented at the Givens Chair Celebration, April 8, 2002.

Nonlinear Optical Interactions

Light-by-Light Scattering

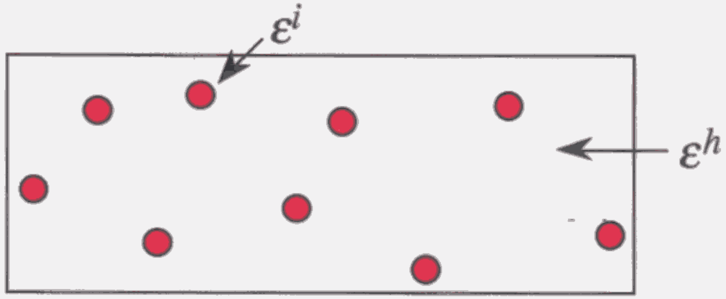


Phase Conjugation by Degenerate Four-Wave Mixing

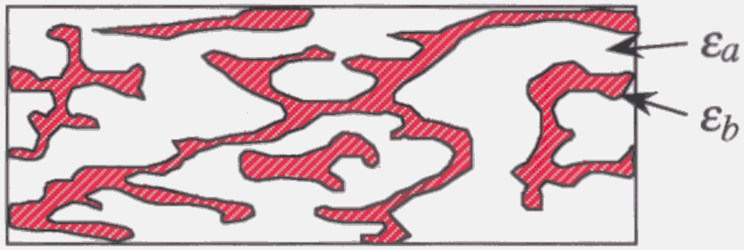


Nanocomposite Materials for Nonlinear Optics

- Maxwell Garnett

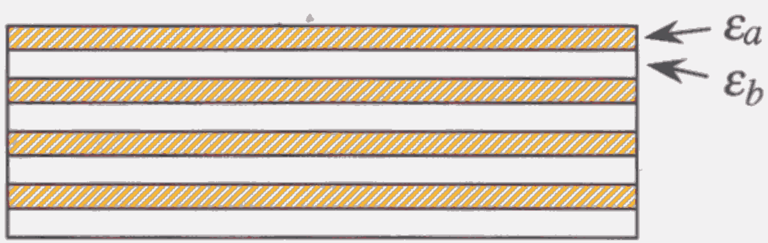


- Bruggeman (interdispersed)



- Fractal Structure

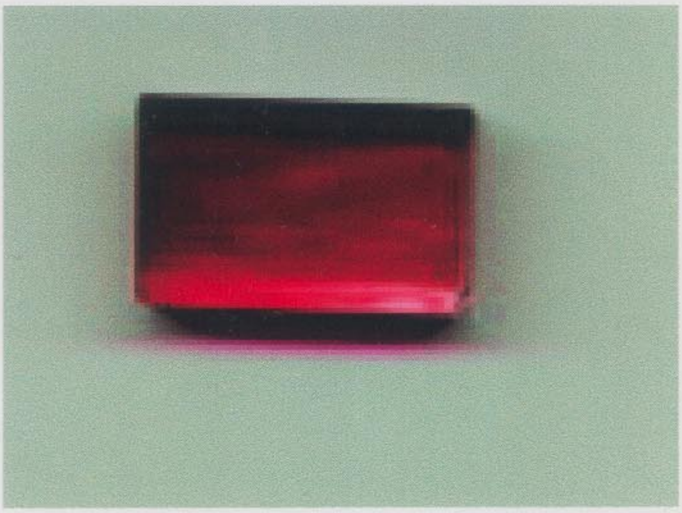
- Layered



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

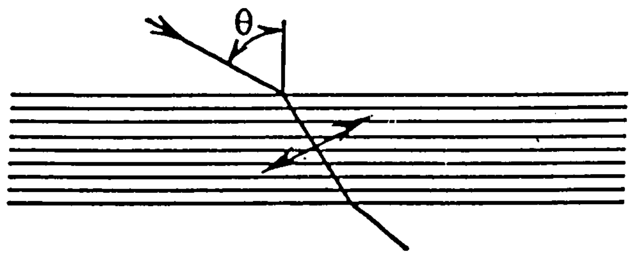
- Composite materials can possess properties very different from their constituents.

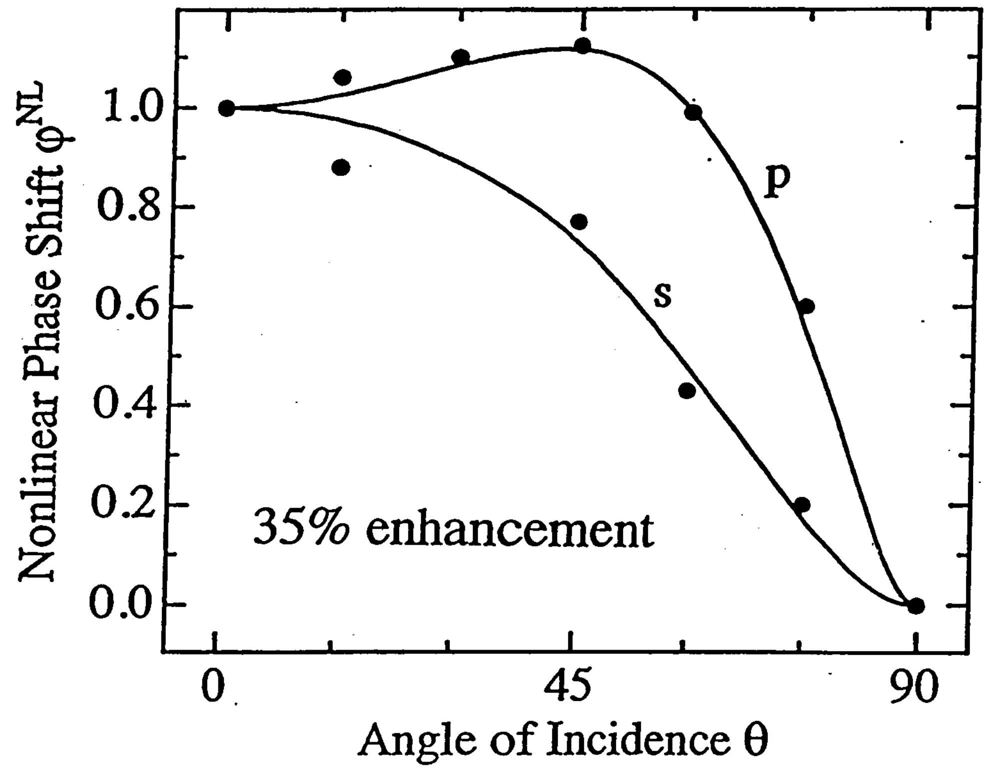
- Red color is because the material absorbs very strongly at the surface plasmon frequency (in the blue) -- a consequence of local field effects.

First Demonstration of Enhanced NLO Response

Alternating layers of TiO_2 and the conjugated polymer PBZT.

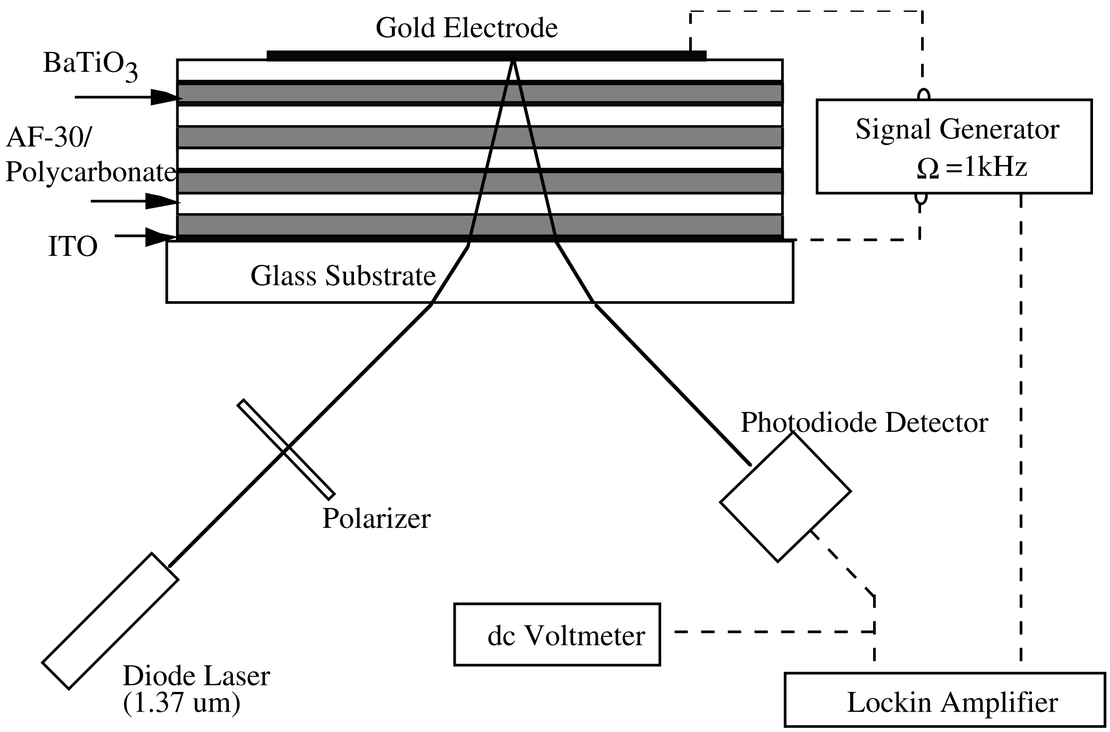
Measure NL phase shift as a function of the angle of incidence.





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.

“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

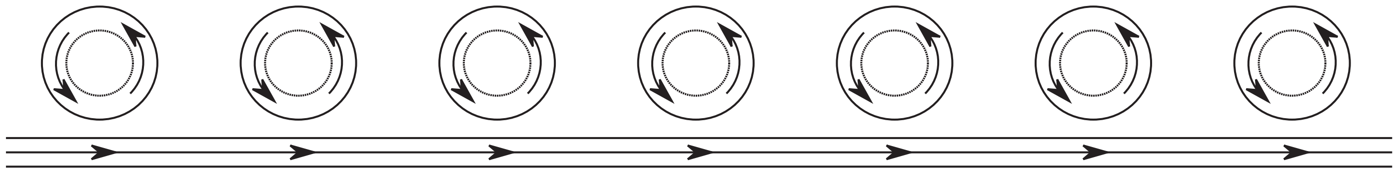
Nanofabrication

- Materials (artificial materials)
- Devices

(distinction?)

NLO of SCISSOR Devices

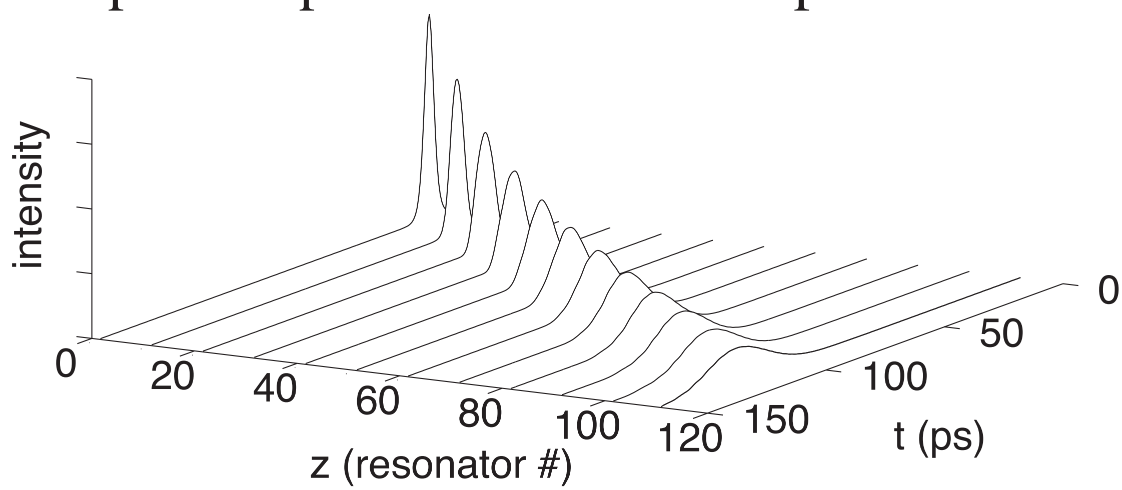
(Side-Coupled Integrated Spaced Sequence of Resonators)



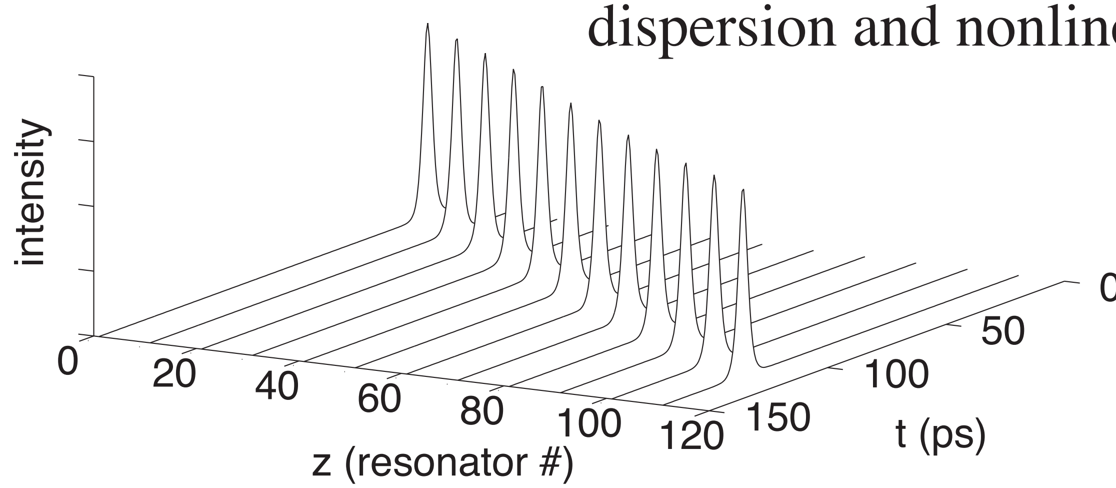
Shows slow-light, tailored dispersion, and enhanced nonlinearity

Optical solitons described by nonlinear Schrodinger equation

- Weak pulses spread because of dispersion

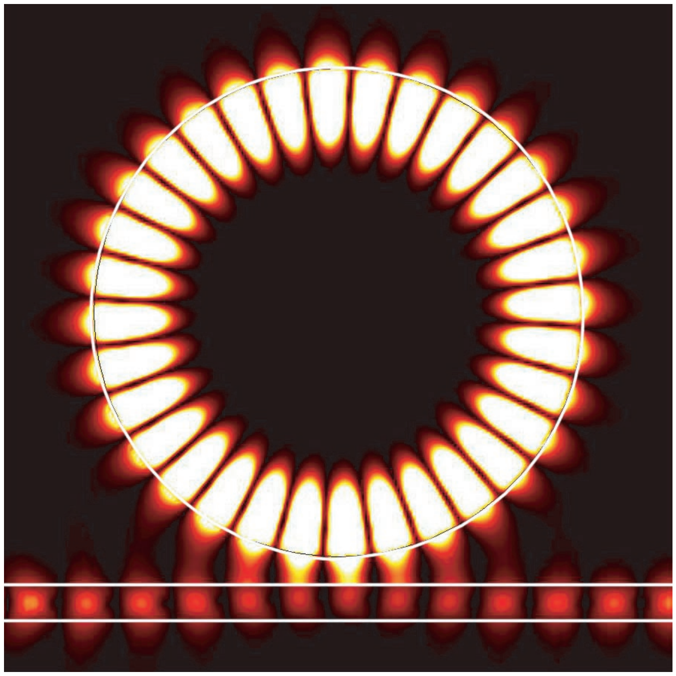


- But intense pulses form solitons through balance of dispersion and nonlinearity.



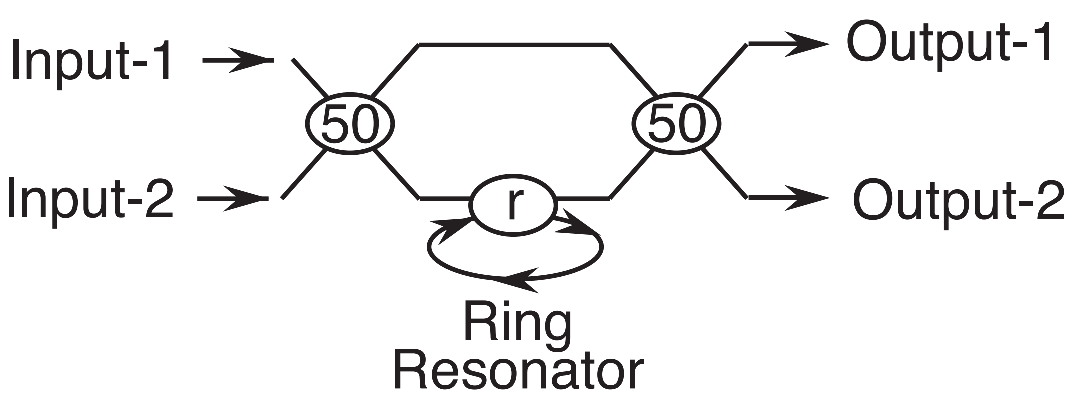
Ultrafast All-Optical Switch Based On Arsenic Triselenide Chalcogenide Glass

- 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

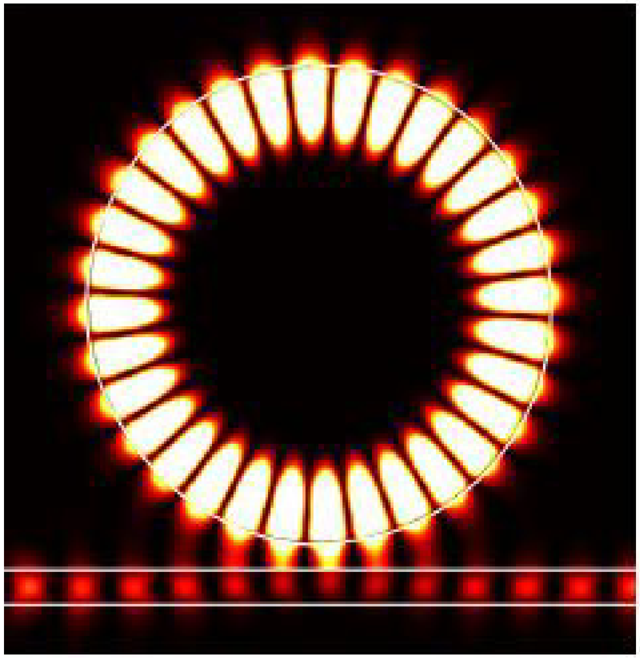
Photonic Devices for Biosensing

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

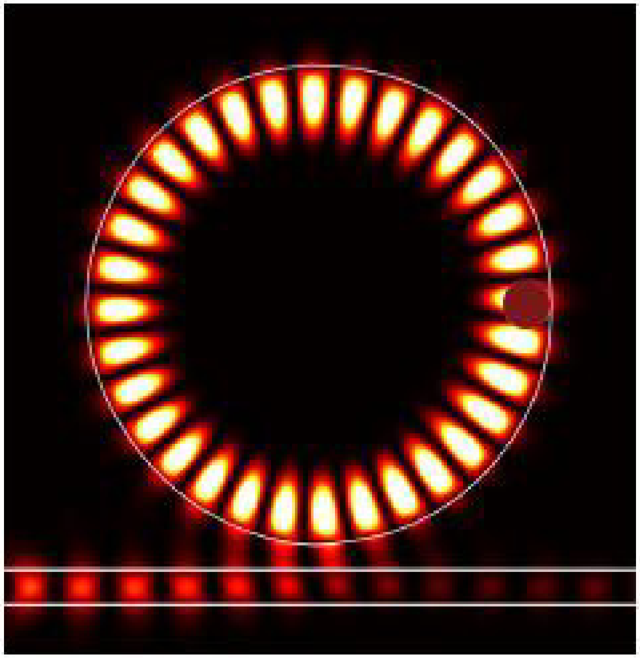
Approach:
Utilize high-finesse whispering-gallery-mode disk resonator.

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

Simulation of device operation:



Intensity distribution in absense of absorber.

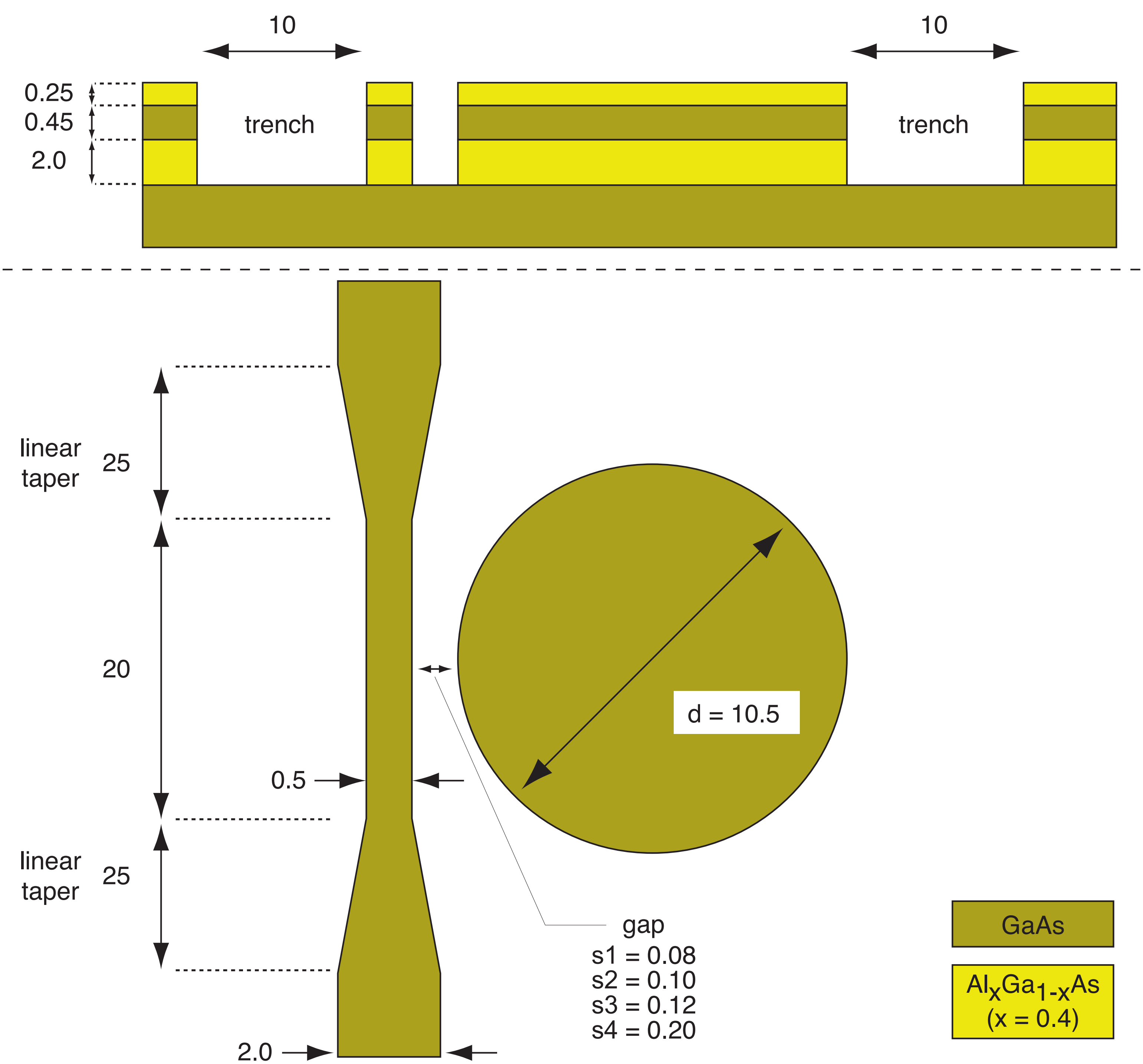


Intensity distribution in presence of absorber.

FDTD

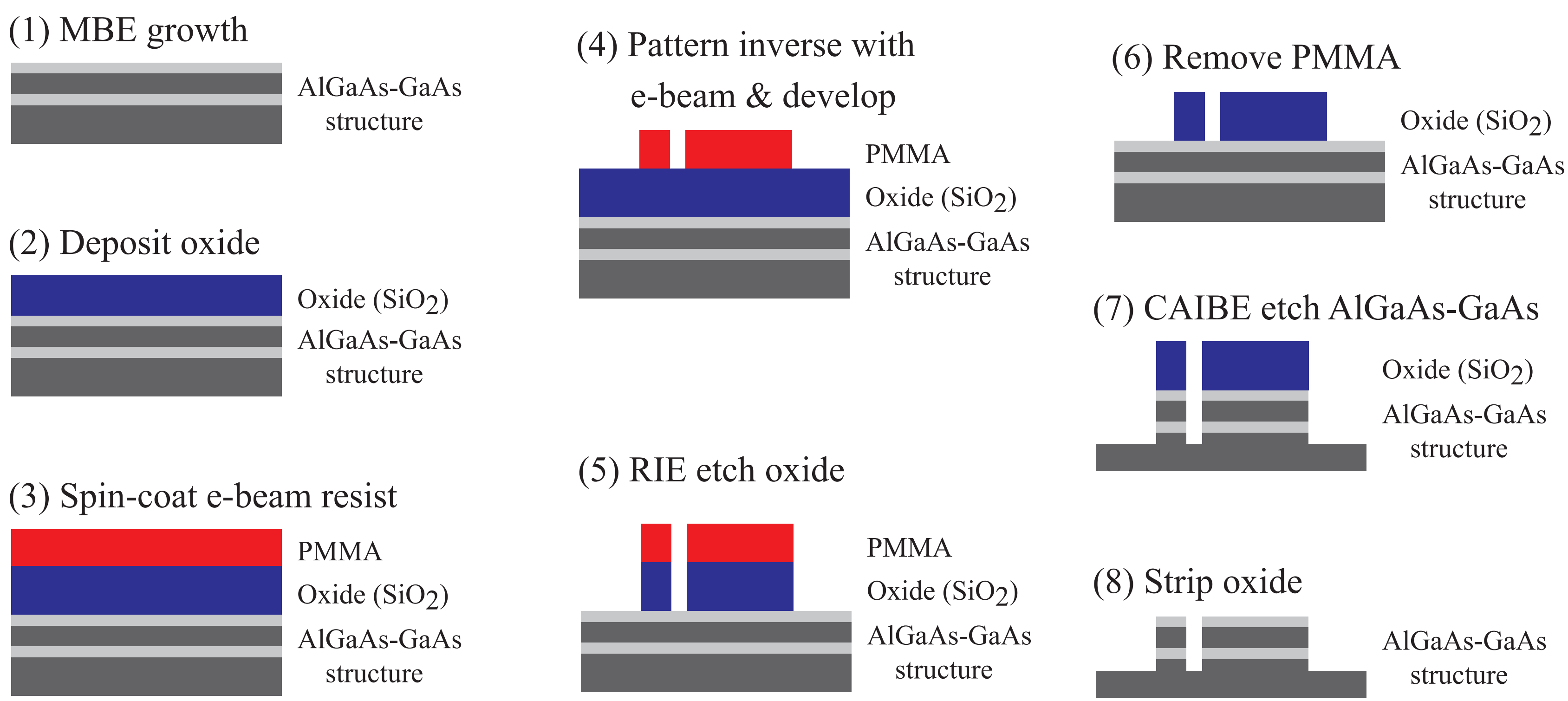
Microdisk Resonator Design

(Not drawn to scale)
All dimensions in microns



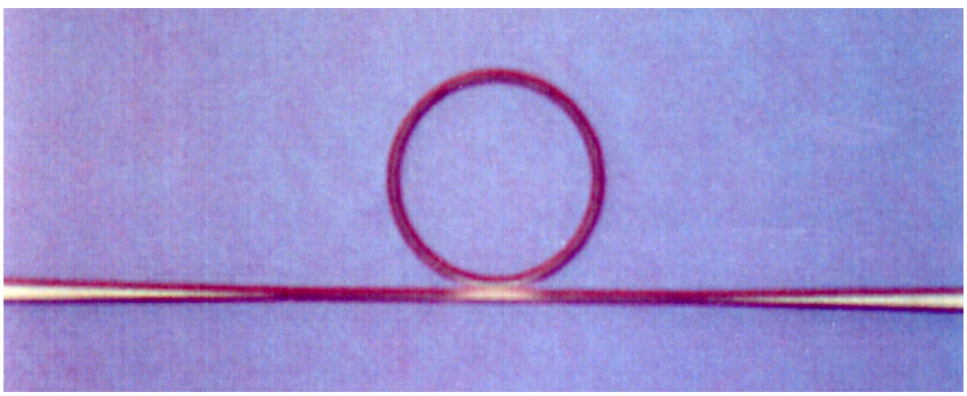
J. E. Heebner and R. W. Boyd

Photonic Device Fabrication Procedure



RWB - 10/4/01

Nonlinear Optical Loop-De-Loop



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

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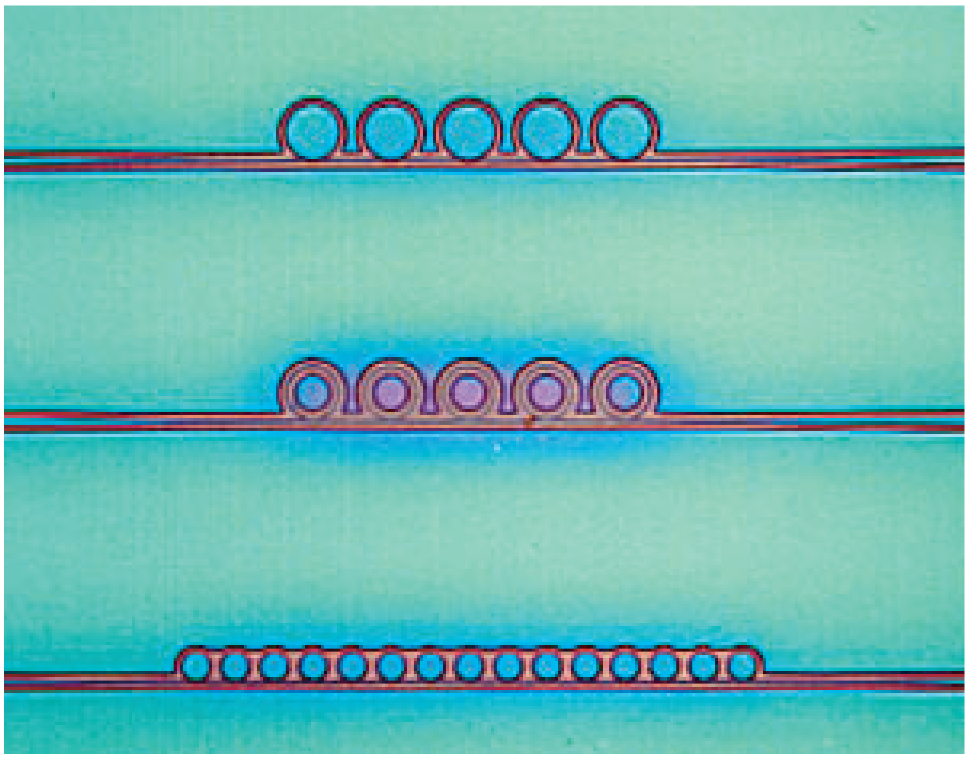

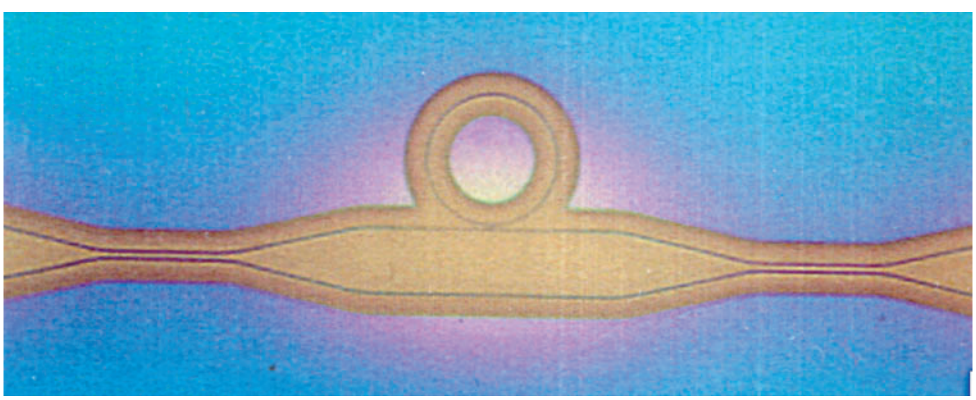

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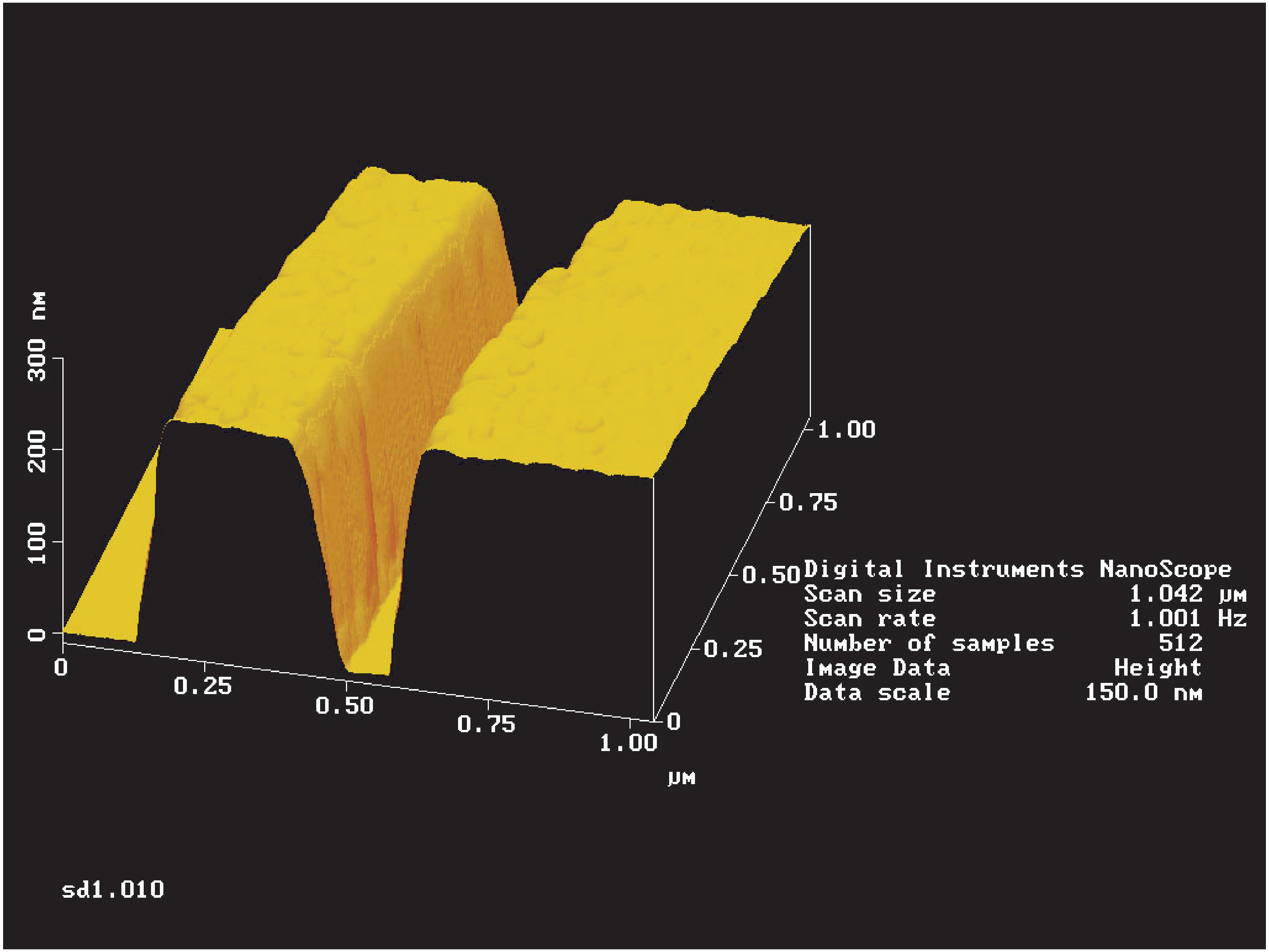
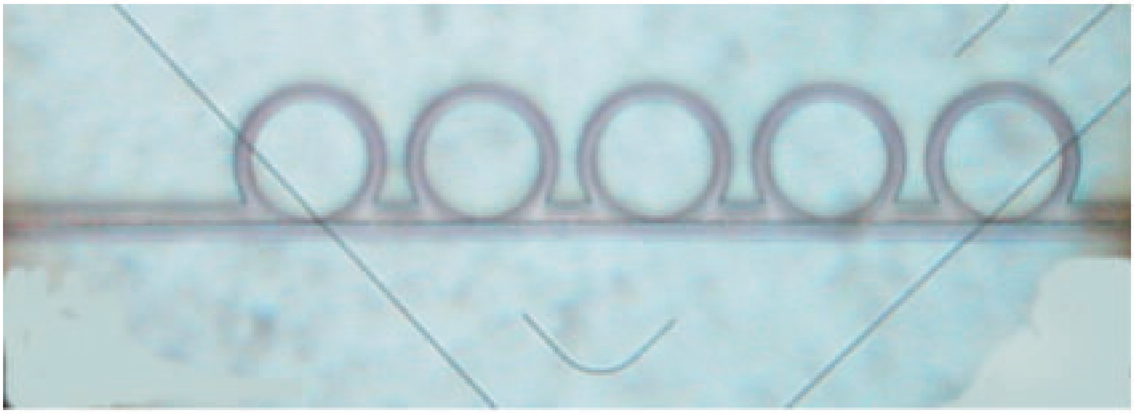
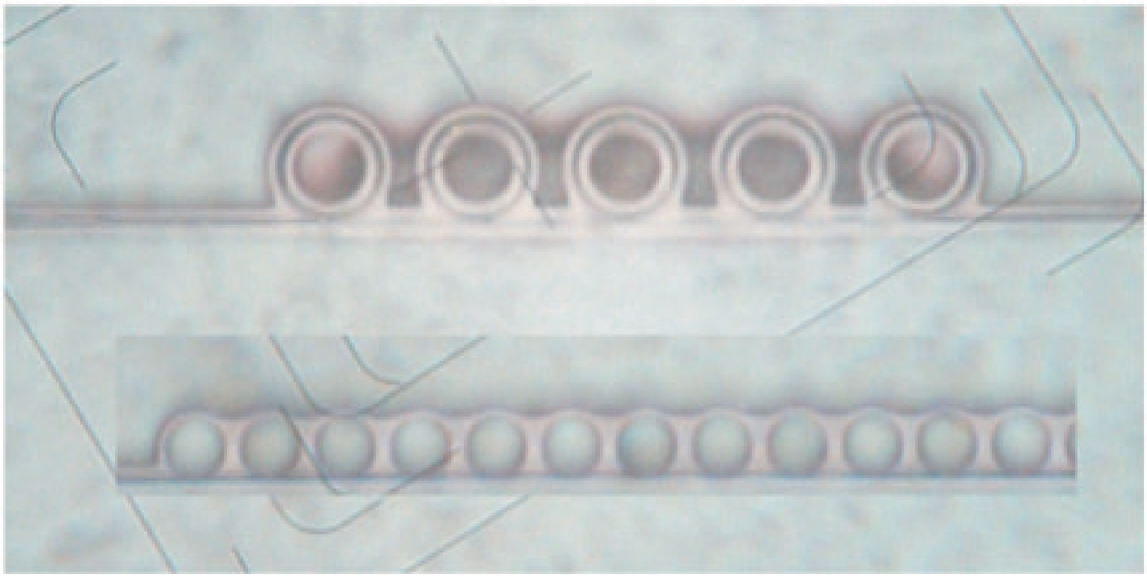
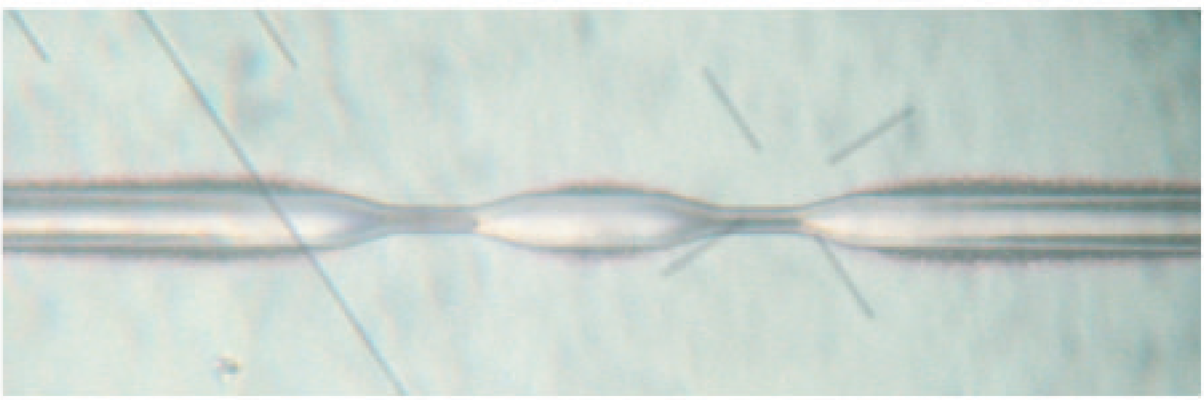

300
200
100
0
nm
0
0.25
0.50
0.75
1.00
µm
0
0.25
0.50
0.75
1.00
Digital Instruments NanoScope
Scan size 1.042 µm
Scan rate 1.001 Hz
Number of samples 512
Image Data Height
Data scale 150.0 nm
sd1.010

a

Photonic Devices in GaAs/AlGaAs







Some Underlying Issues in Nonlinear Optics

- Self-Assembly/Self-Organization in Nonlinear Systems
- Stability vs. Instability (and Chaos) in Nonlinear Systems

Experimental Study of Soliton Propagation through 40 km of Dispersion-Decreasing Fiber

Andrew J. Stentz, Robert W. Boyd, University of Rochester
Alan F. Evans, Corning Inc.

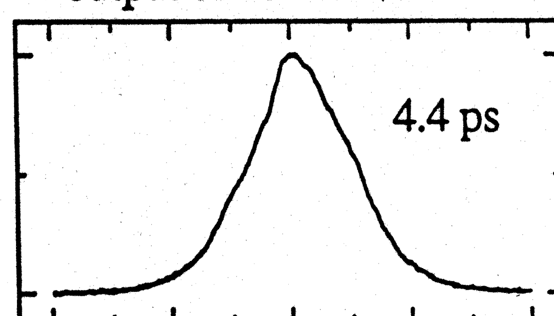
- Solitons propagate without spreading because of exact balance between group velocity dispersion (GVD) and self-phase modulation (SPM).

$$i\frac{\partial U}{\partial \xi} = \mathrm{sgn}(\beta_2)\frac{1}{2}\frac{\partial^2 U}{\partial \tau^2} - N^2|U|^2 U$$

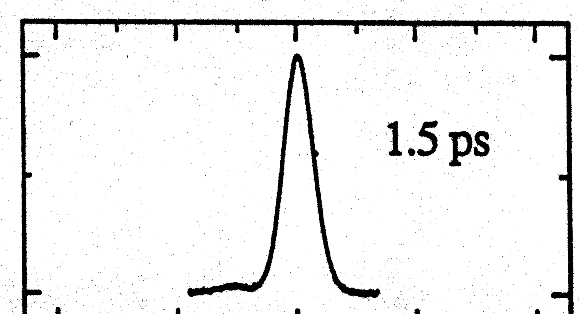
- Even the small attenuation (0.2 dB/km) of communications fibers can upset this local balance and lead to pulse spreading.

- Solution is to use a tapered fiber (15% in 40 km) so that the GVD decreases at the same rate as the pulse energy.

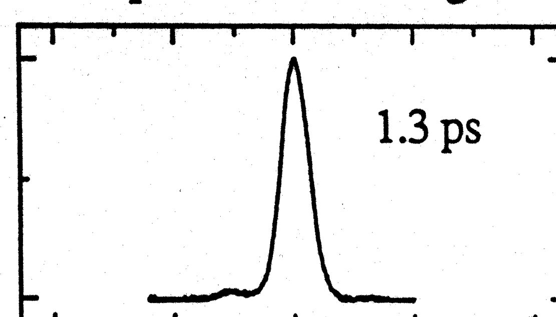
output of conventional fiber



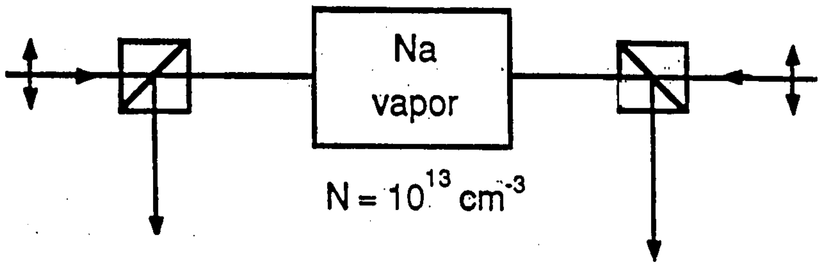
input

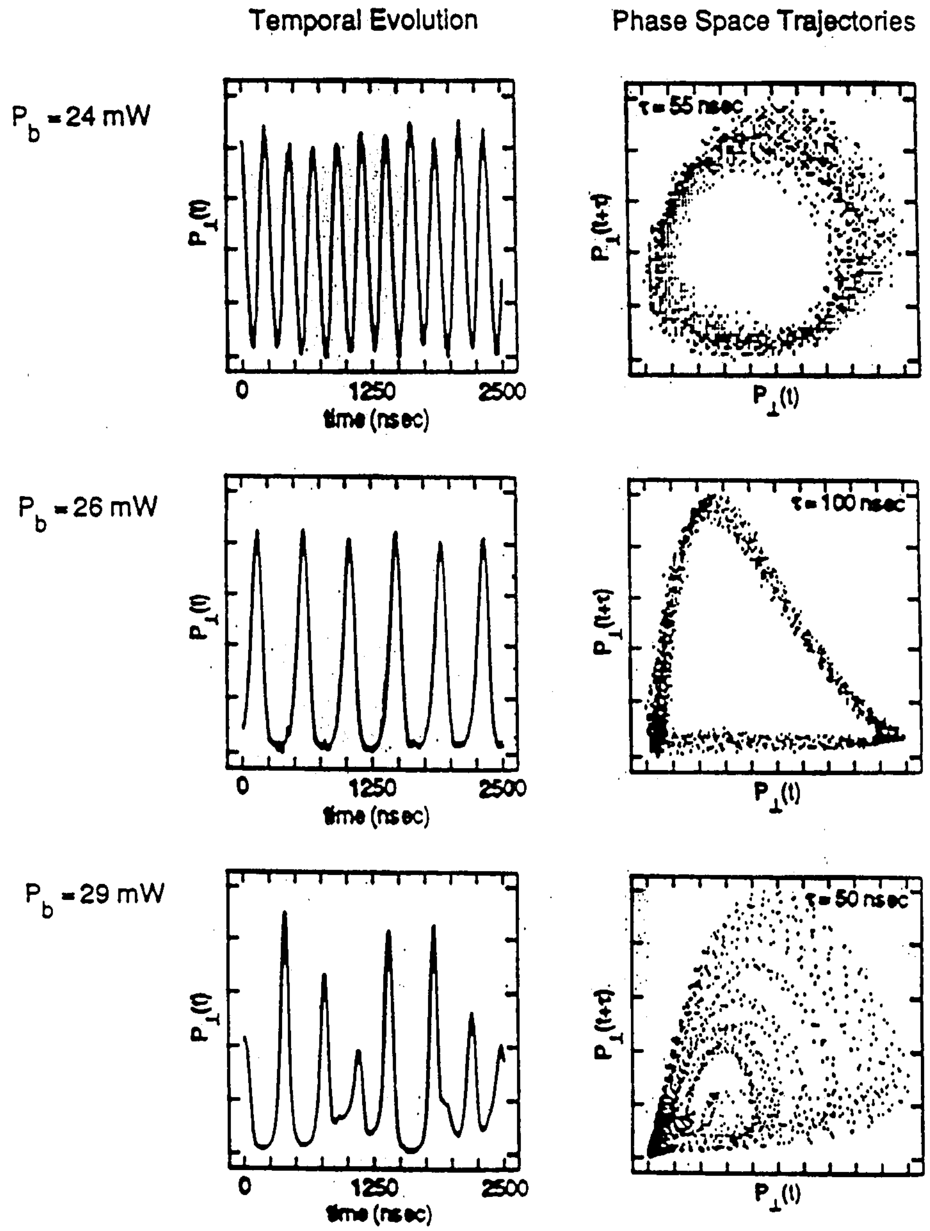


output of dispersion-decreasing fiber



Chaos in Sodium Vapor

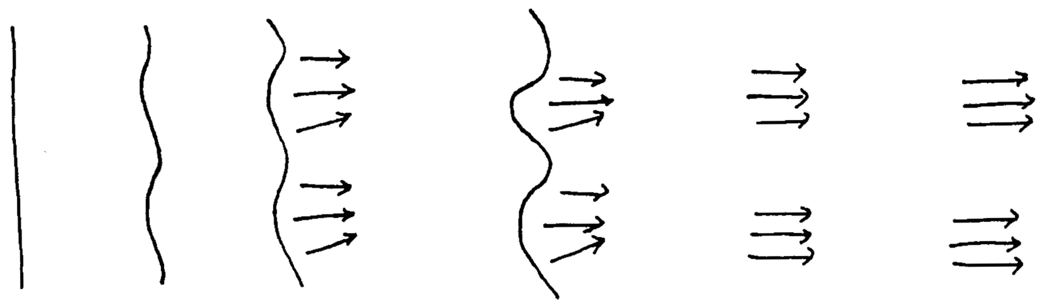




PRL 58, 2432 (1987); 61, 1827 (1988); 64 1721 (1990).

Laser Beam Filamentation

Spatial growth of wavefront perturbations



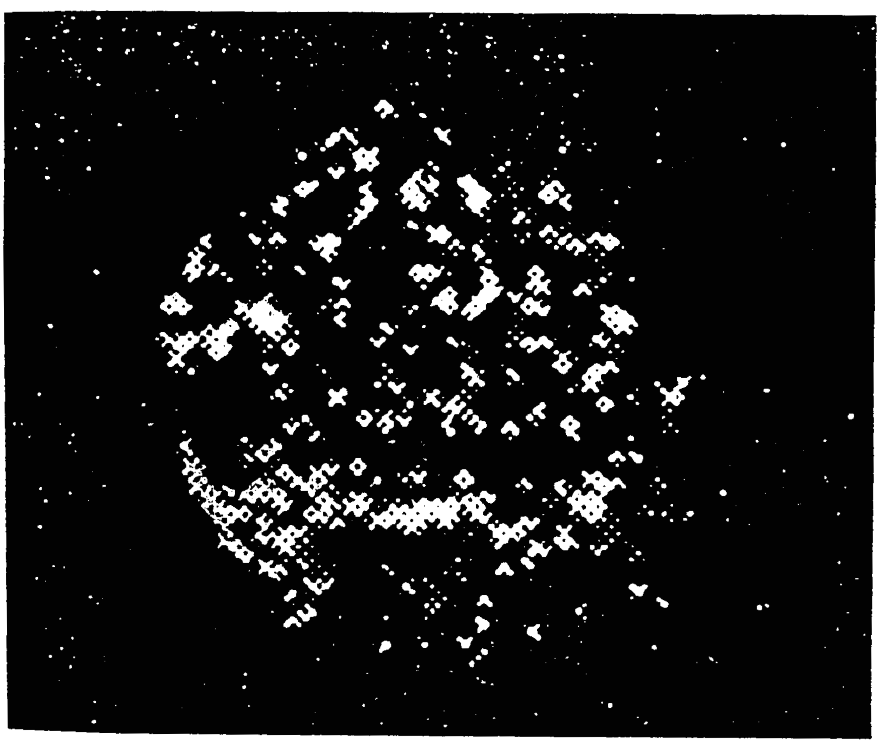
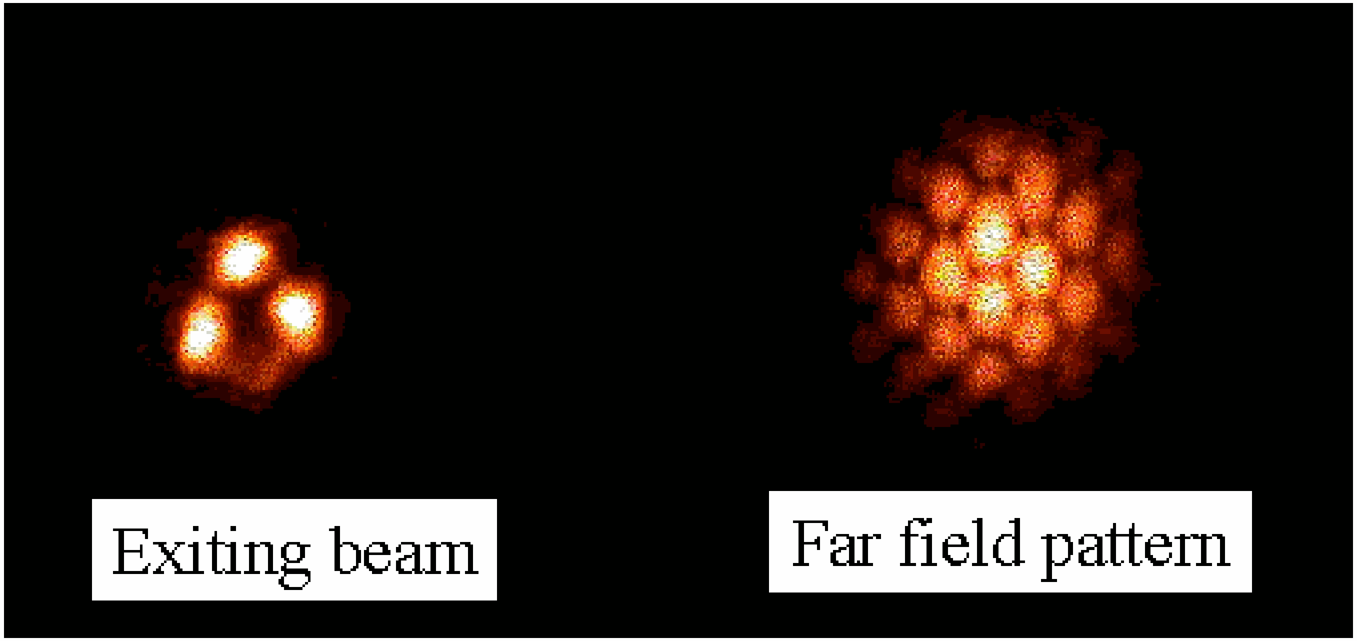


Fig. 17.2 Image of small-scale filaments at the exit windows of a CS_2 cell created by self-focusing of a multimode laser beam. [After S. C. Abbi and H. Mahr, *Phys. Rev. Lett.* 26, 604 (1971).]

Honey Comb Pattern Formation

Robert W. Boyd and C. R. Stroud, Jr., University of Rochester

Output from cell with single gaussian beam input



Quantum image?

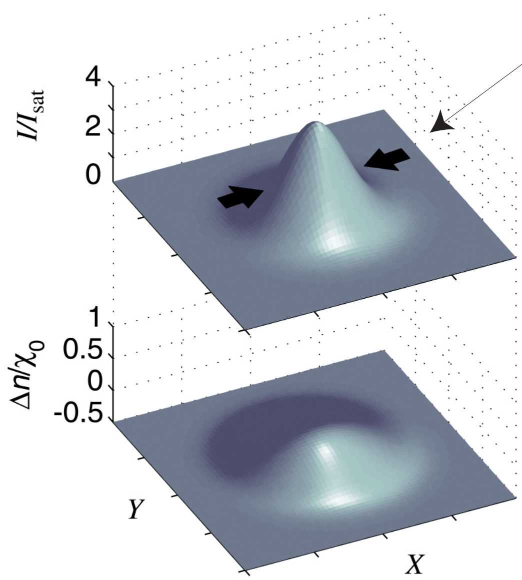
Input power 150 mW
Input beam diameter 0.22 mm
$\lambda = 588.995$ nm

Sodium vapor cell
T = 220° C

Spontaneous Pattern Formation in Sodium Vapor

A sodium vapor may be thought of as a medium composed of two-level atoms. Light whose frequency is near the atomic transition frequency experiences a refractive index n which depends strongly on the intensity I:

beam will narrow due to lens-like refractive index profile



induced refractive index is like a positive lens

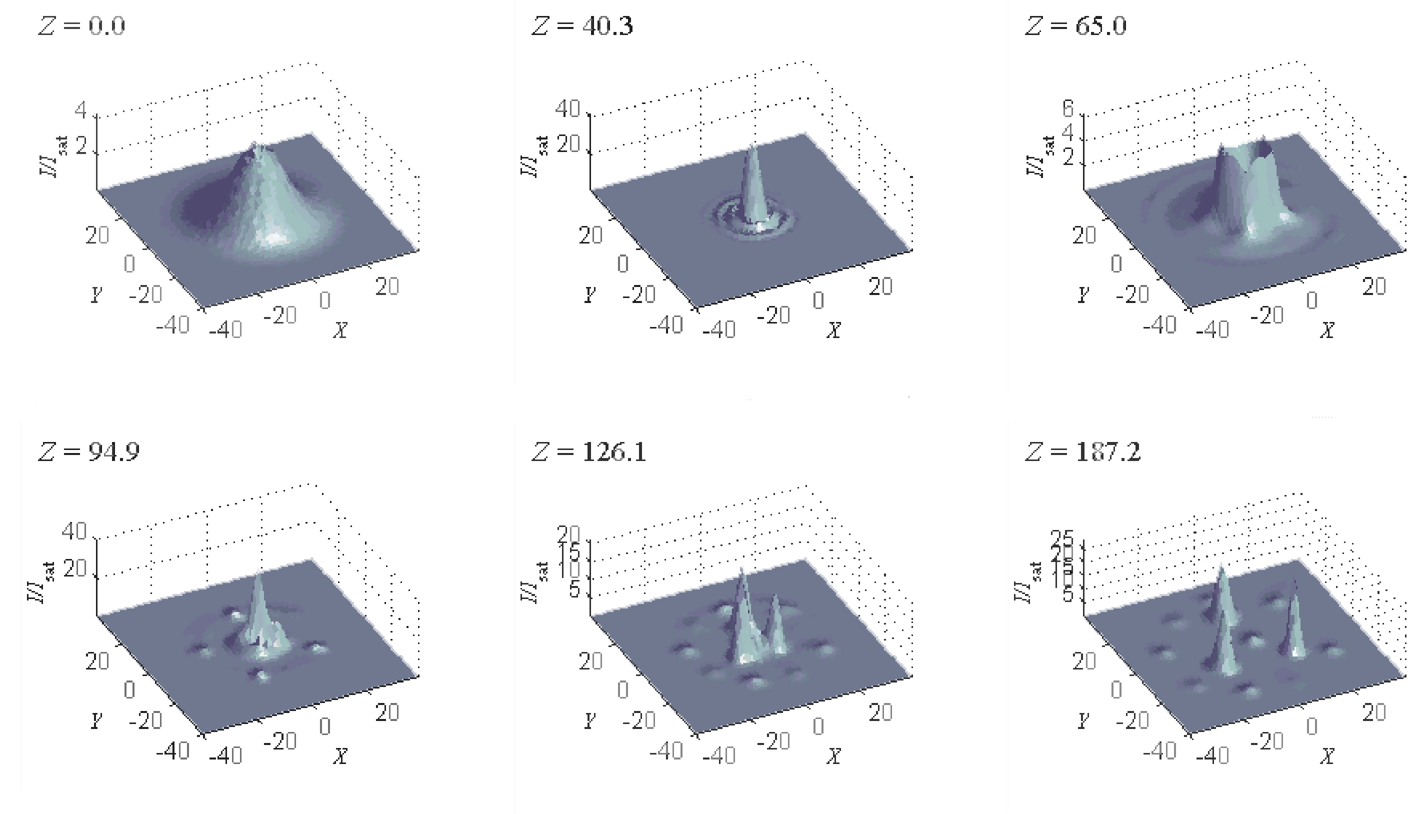
$$n = 1 + \quad n$$

$$1 + \frac{1}{2}\,\frac{0}{1 + I/I_{sat}}$$

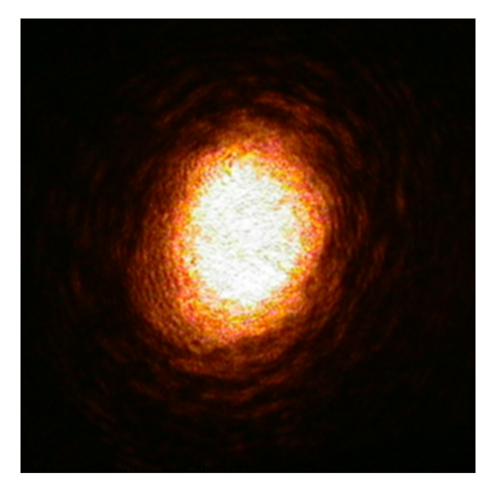
Since light refracts in the direction of increasing index, in a medium with negative saturable nonlinearity it refracts toward regions of higher intensity. This causes smooth beams to narrow or self-focus. But it also tends to destabilize a beam as small amplitude fluctuations grow due to local self-focusing. Thus beams with even small amplitude noise can spontaneously split into two or more separate beams.

**For sodium at 200°C, $_0$ -0.05 and I_{sat} 6 mW/cm²*

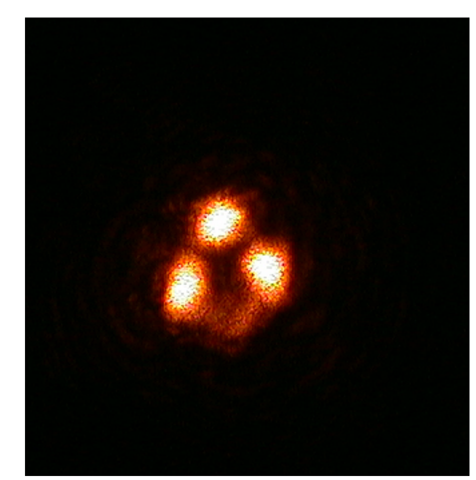
A simulation of spontaneous break-up into 3 stable beams:



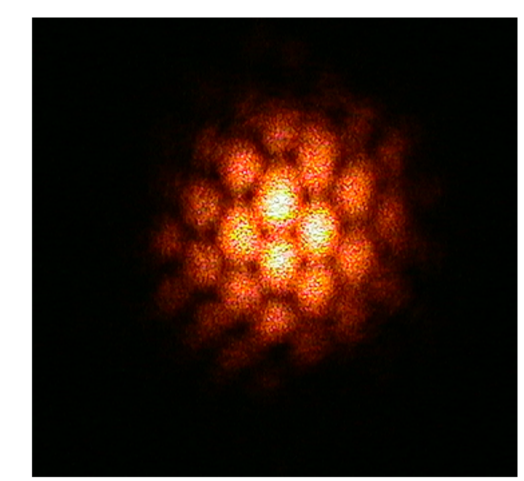
Experimental observation of spontaneous break-up resulting in a striking far-field pattern:



beam entering sodium



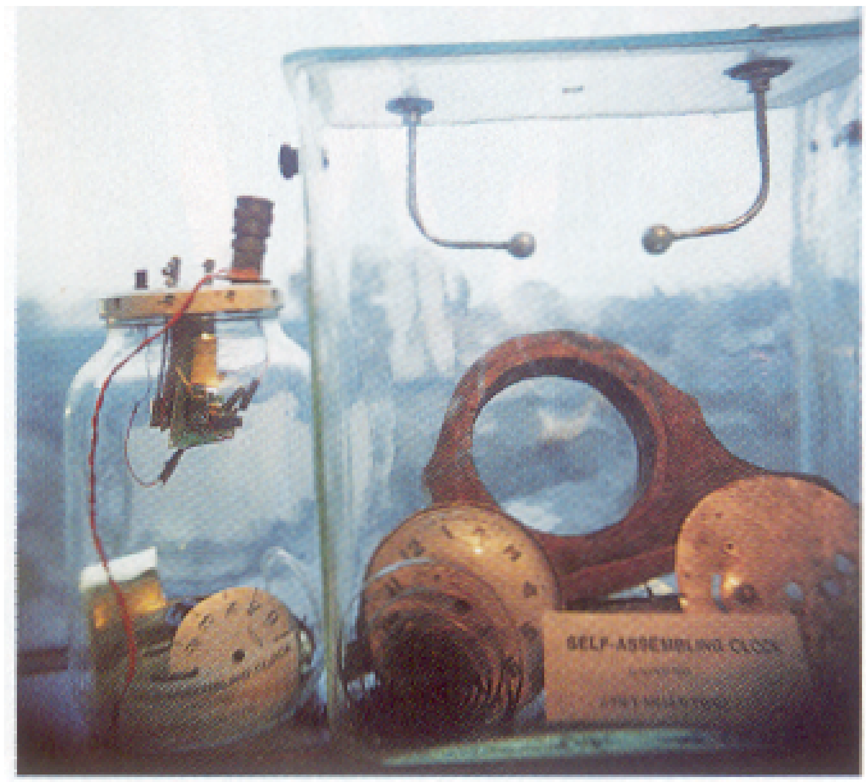
beam leaving sodium



far-field pattern

Pictures taken by R. Bennink, S. Lukishova, and V. Wong.

Experiment in Self Assembly



Joe Davis, MIT