Enhanced Linear and Nonlinear Optical Phase Response of Microring Resonators for Engineerable Photonic Media

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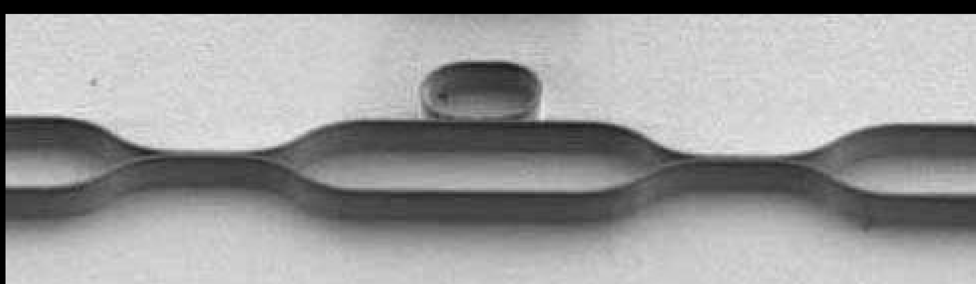


The Institute of OPTICS

Motivation

Densely integrated & ultrafast photonics on a chip

- Switching, logic, and pulse manipulation require a fast nonlinear optical mechanism that is sensitive with low absorptive dissipation.

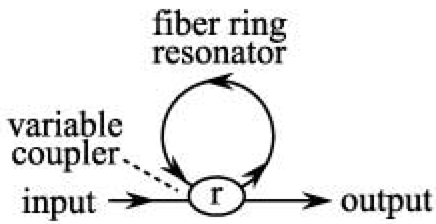
- Compared with other nonlinearities, the Kerr effect below half-gap is ultrafast and dissipates little heat (limited by 3-photon absorption).

- Problem is that waveguide devices have required >5 mm of path length to achieve π phase shifts.

- Side-coupled ring resonators: enhance the nonlinearity while decreasing bandwidth (but from 200 THz to 1 THz).

- **Can resonators reduce this length scale by 100X ? or even 1000X ?**

Variable Coupler Fiber Ring Resonator



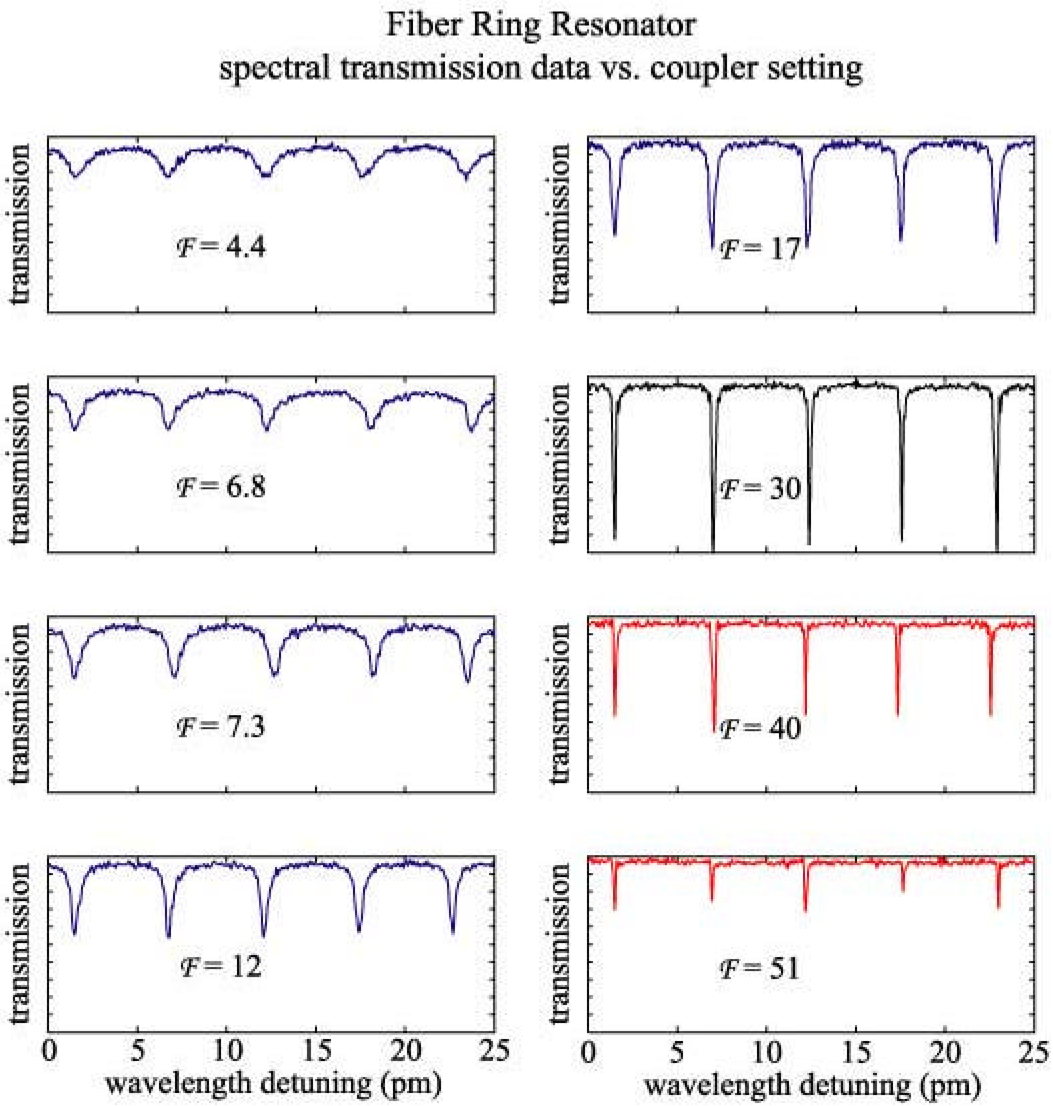
combined splice and coupler loss
~10% (0.45 dB)

<u>3 regimes:</u>

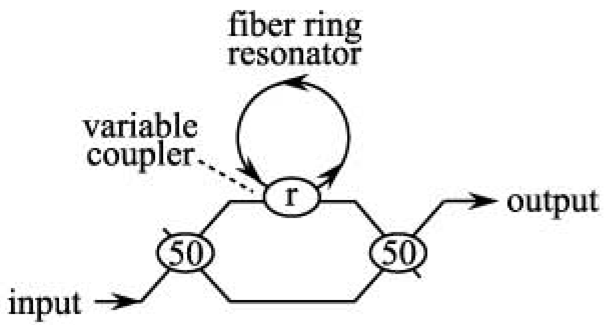
Overcoupled (coupling governs finesse)

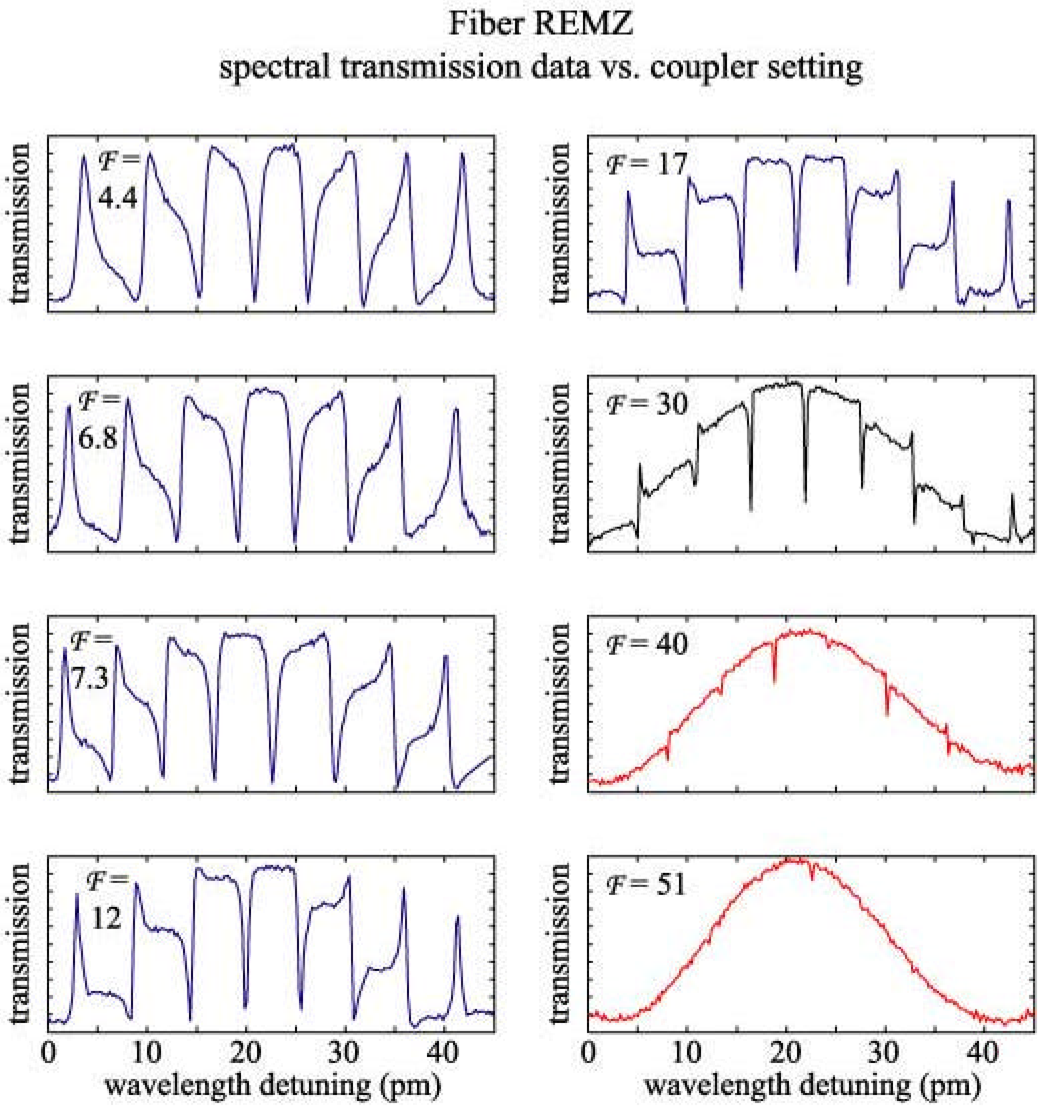
Critically coupled (loss = coupling)

Undercoupled (loss governs finesse)



Variable Coupler Fiber Resonator Spectral Phase





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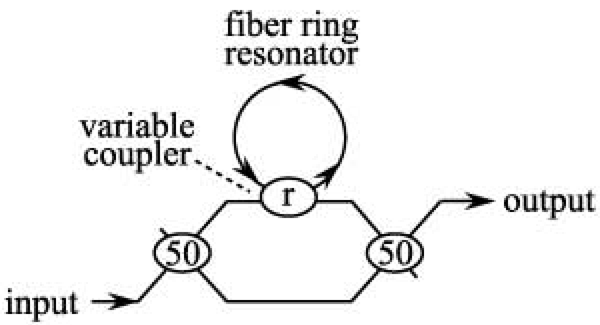
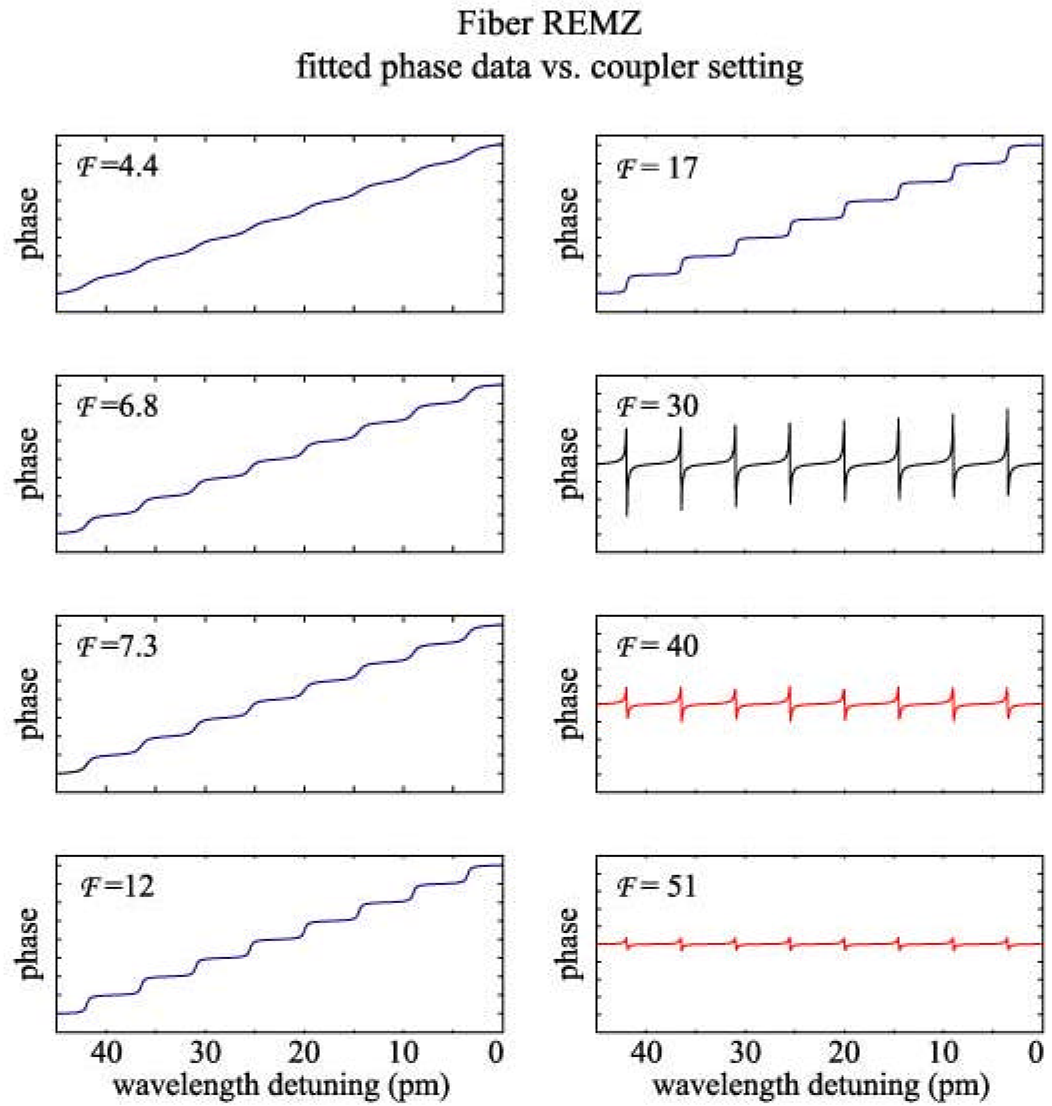
Variable Coupler Fiber Resonator Spectral Phase





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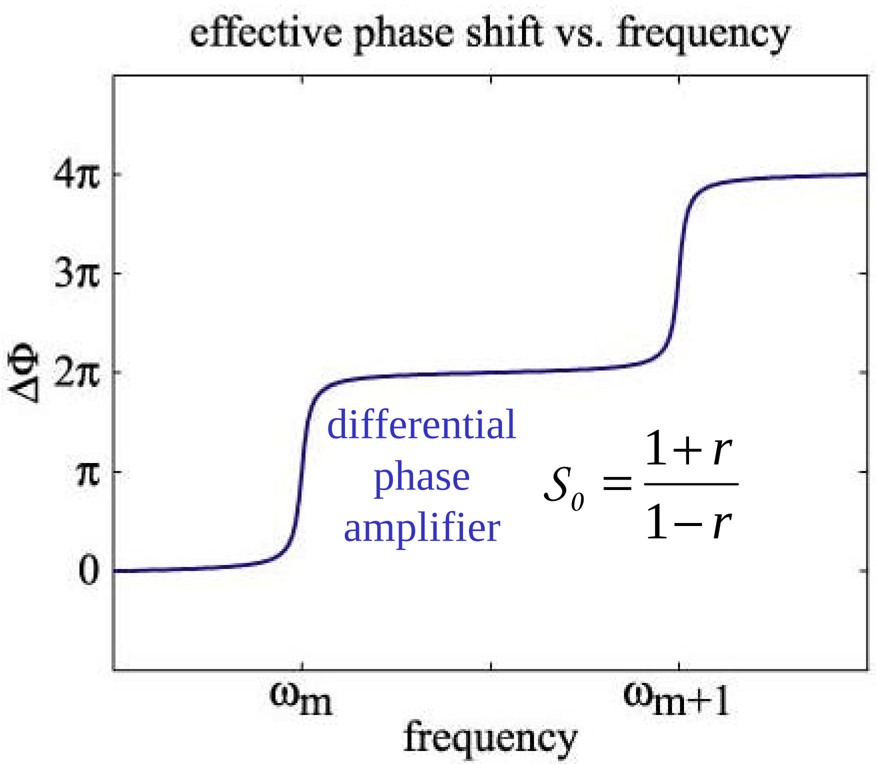
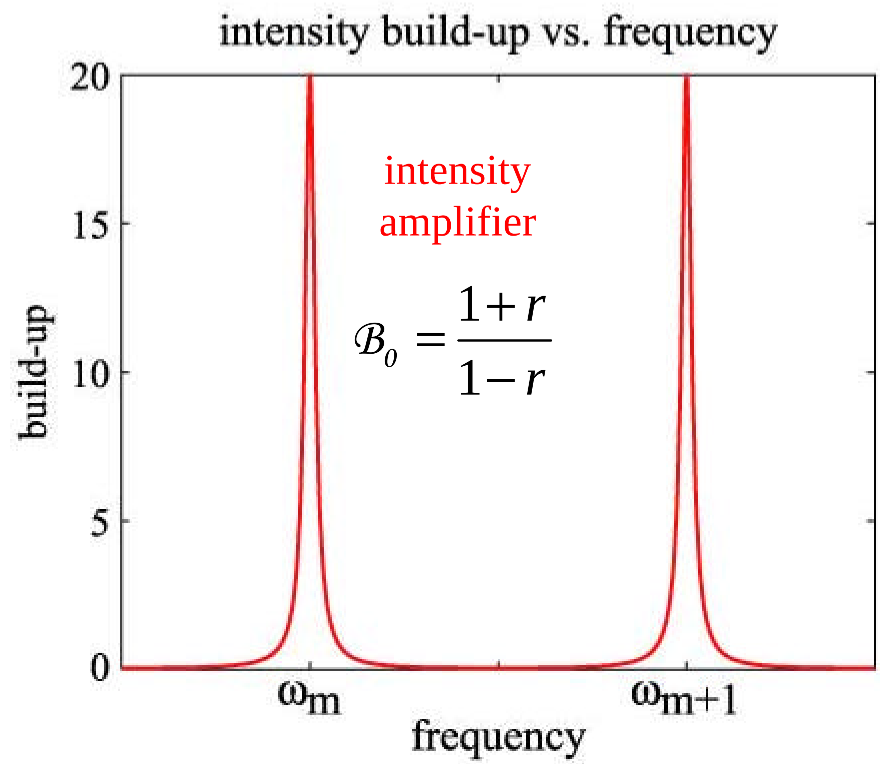
"Optical Transmission Characteristics of Fiber Ring Resonators"
Heebner, Schweinsberg, Wong, Boyd, Accepted J. Quant. Elec., (2004).

Phase Sensitivity & Intensity Build-Up

The effective phase shift is sensitively dependent on frequency near resonance (related to increased group delay).

Near resonances, the circulating field experiences a coherent build-up of intensity.



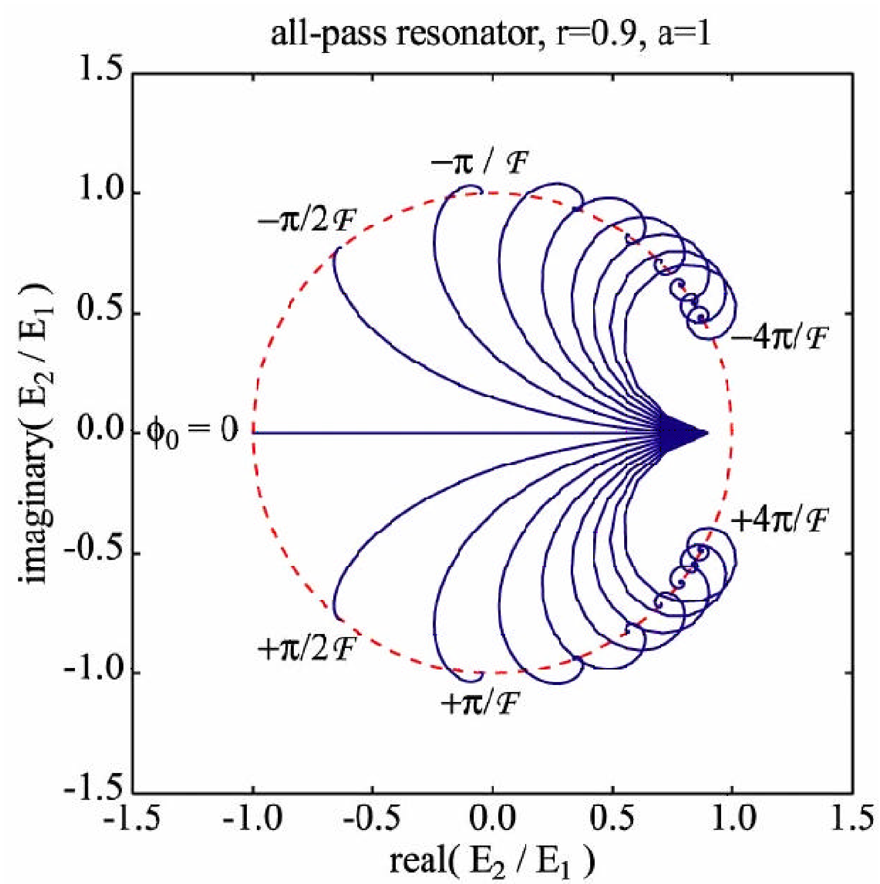


$$\Phi = p + f + 2\arctan\frac{r\sin f}{1-r\cos f}$$

$$\mathcal{B} = \frac{I_c}{I_1} = \frac{1-r^2}{1-2r\cos f + r^2}$$

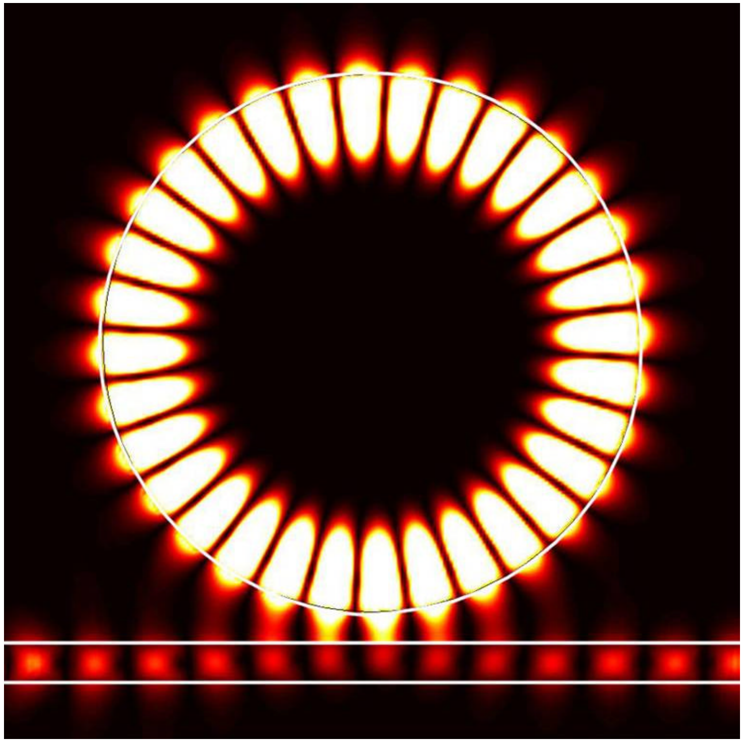
Phase Sensitivity & Intensity Build-Up

Increased Phase Sensitivity



Phasor representation

Intensity Build Up



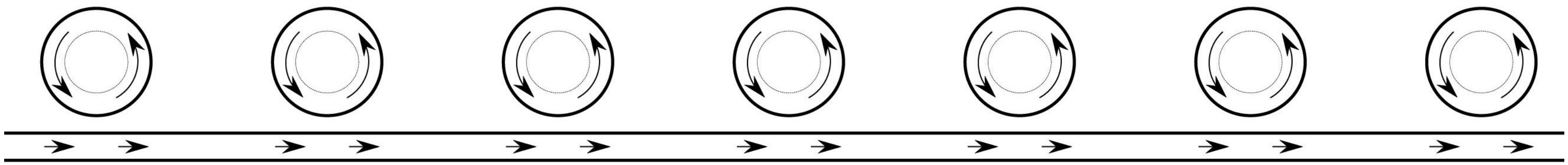
FDTD simulation

Scaling Laws

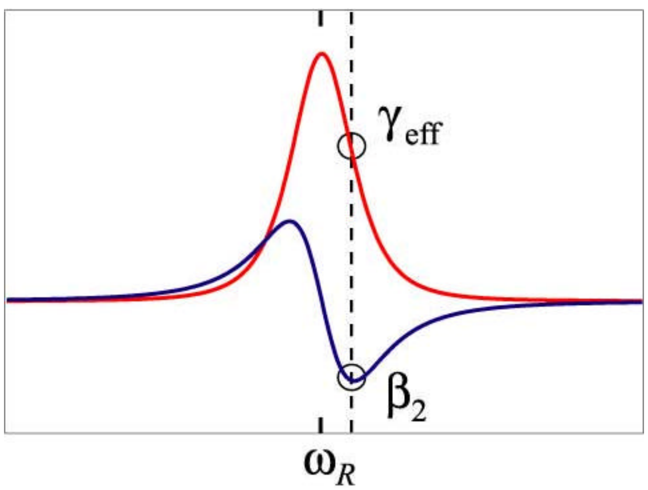
Bandwidth Sensitivity	Q^{-1} Q	sensing
Group velocity = c/n_g Intensity ~ n_g	F^{-1} F	slow light
Linear attenuation ~ αL Nonlinear attenuation (2-photon) ~ $\alpha\, I\, L$	Q QF	loss budgets
GVD = $\Delta\, (n_g/c) / \Delta\omega$ Nonlinear phase ~ $n_2\, I\, L$	QF QF	dispersion-comp, switching, solitons
FWM conversion efficiency ~ $\chi^{(3)}\, I_P\, I_I\, L^2$	Q^2F^2	λ-conversion

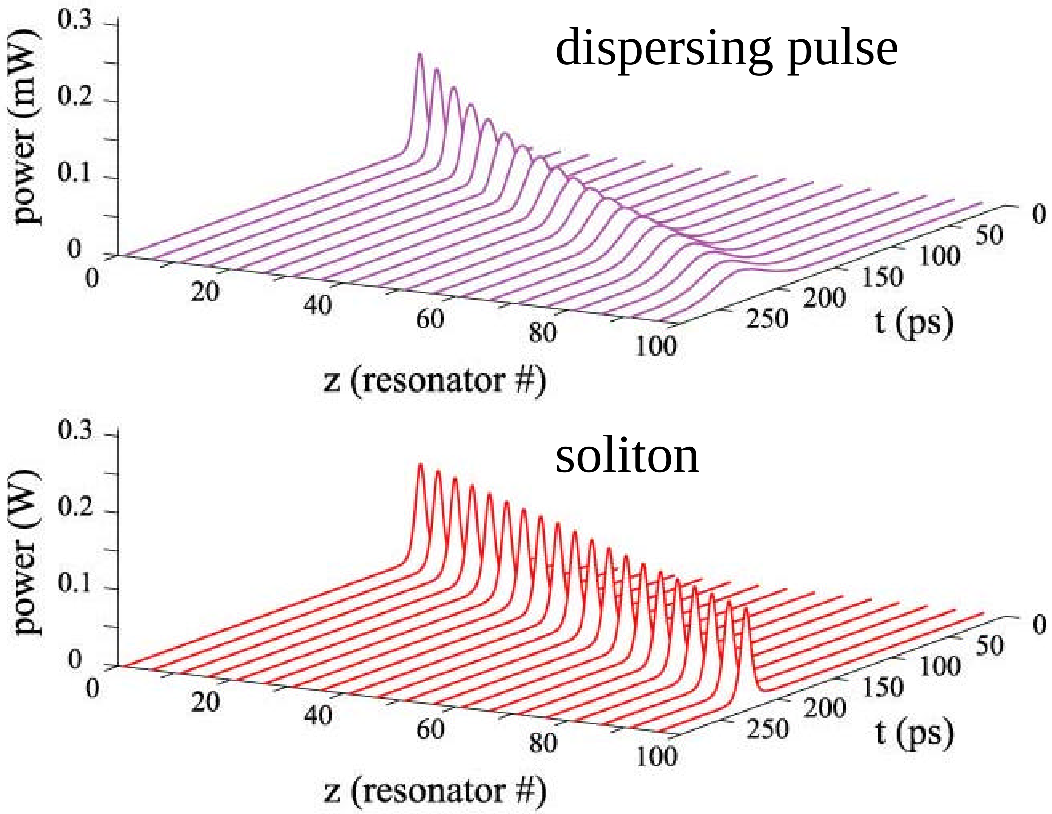
(Figures of merit can be intuited from products and ratios)

SCISSOR Solitons



A balancing of
induced anomalous dispersion and
enhanced self-phase modulation

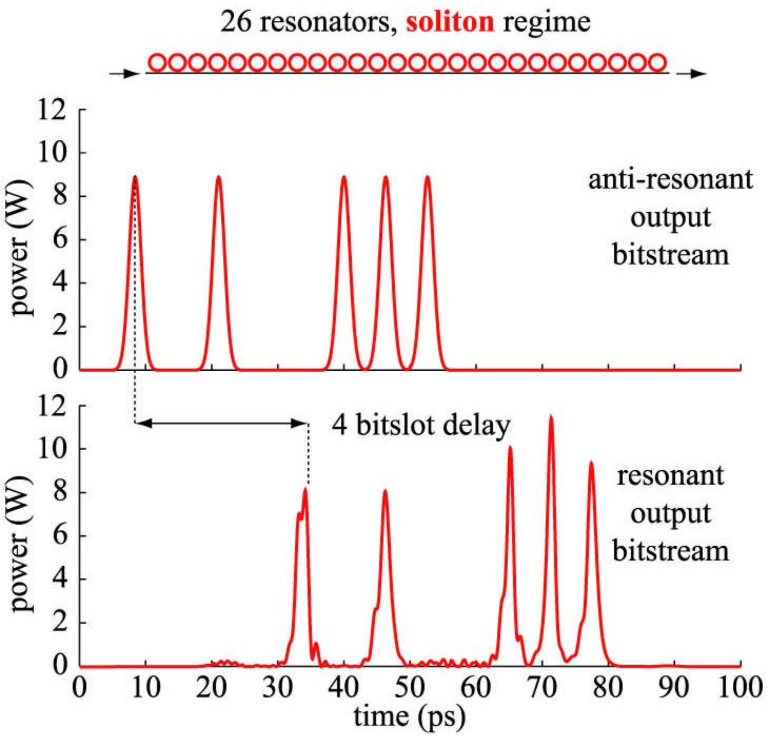




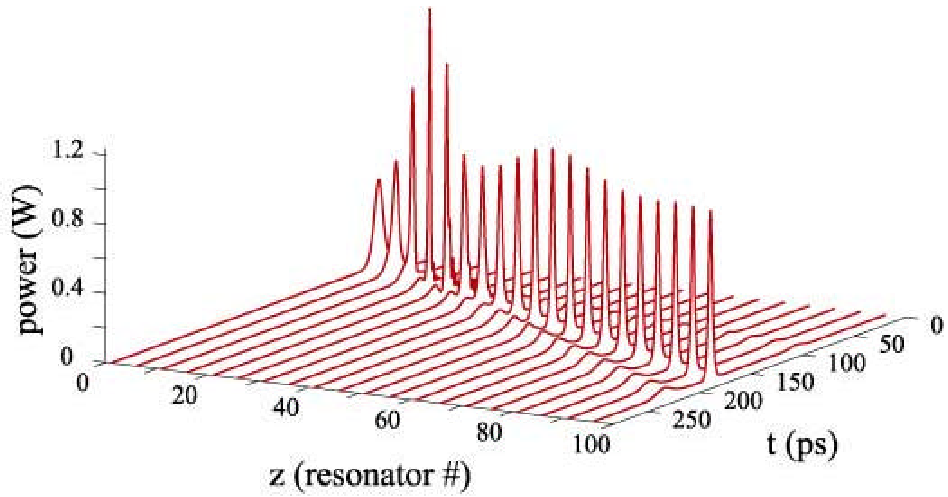
"SCISSOR Solitons & other propagation effects in microresonator modified waveguides"
J. E. Heebner, R. W. Boyd, and Q. Park, JOSA B, 19 (2002)

SCISSOR Applications

Delay Lines
- 160 Gb/s
- 4 bitslot delay

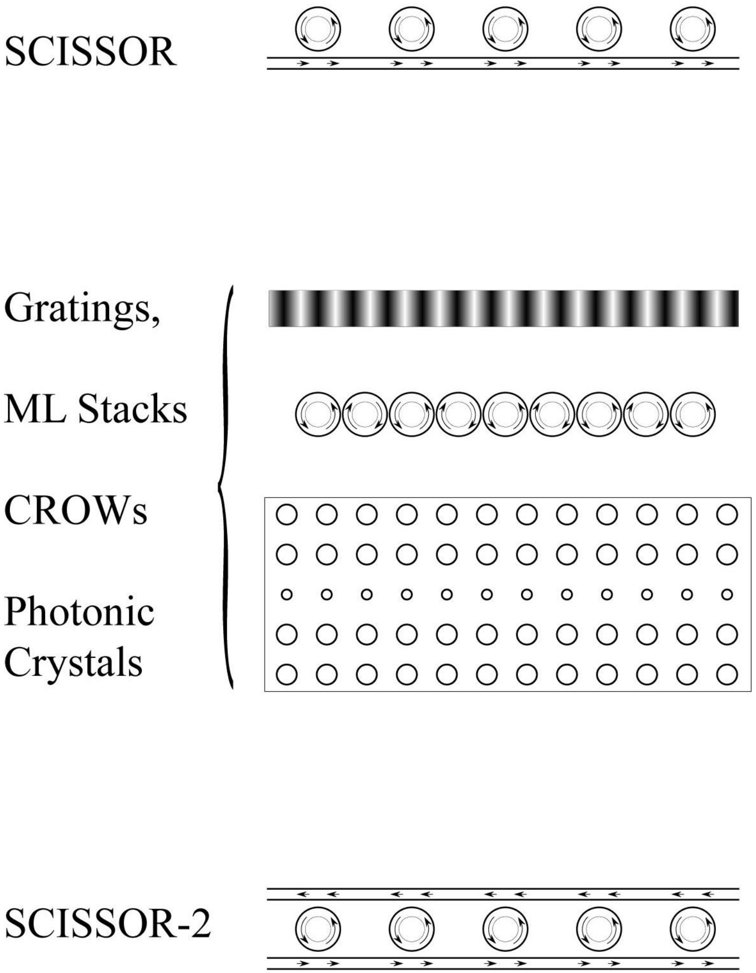


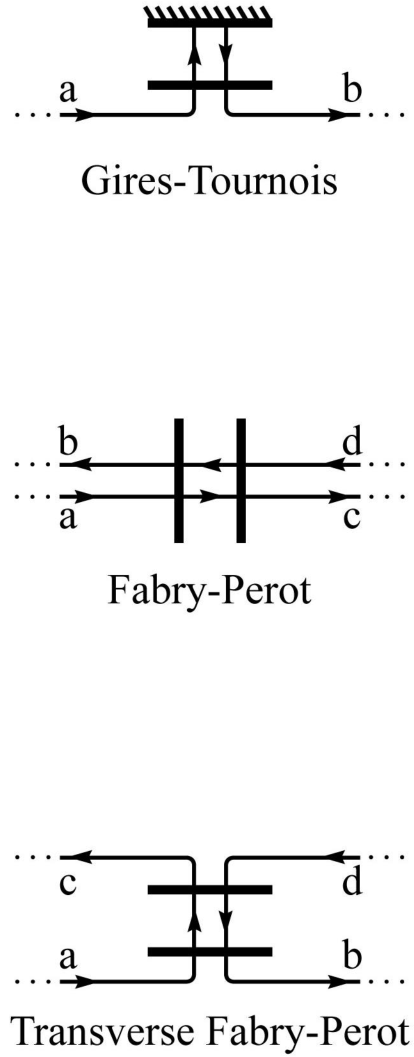
Pulse Compression on a Chip
- High-order soliton splitting (*by self-steepening*)
- Clean, *pedestal-free* pulse compression results

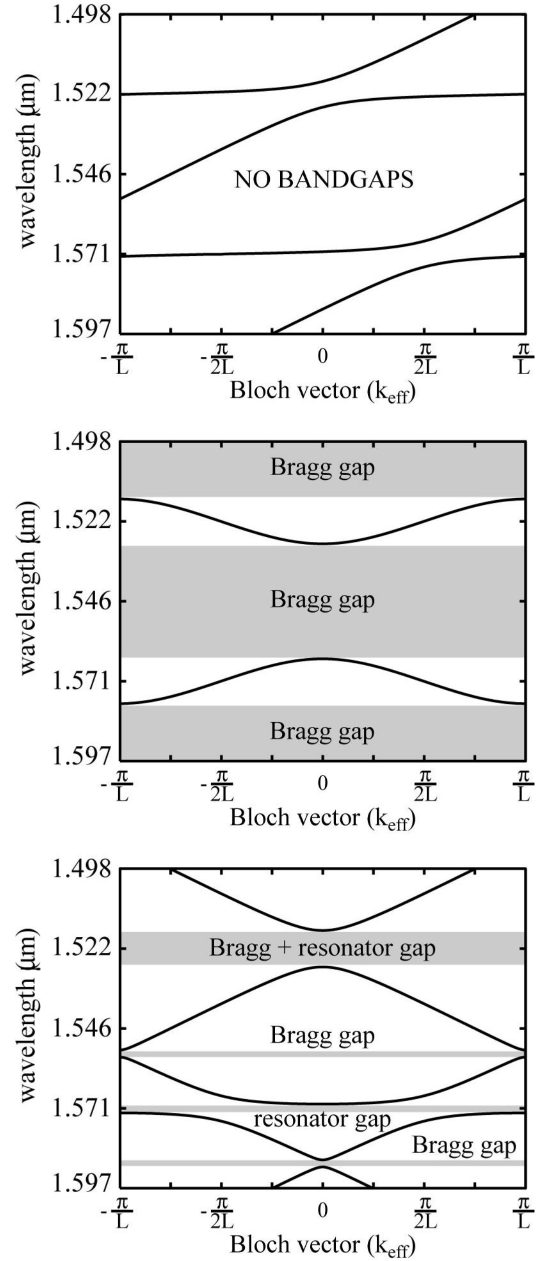


"Strong Dispersive and Nonlinear Optical Properties of Microresonator-Modified Optical Waveguides"
J. E. Heebner and R. W. Boyd, SPIE, 3, 4969-41, (2003)

SCISSORs & Photonic Crystals

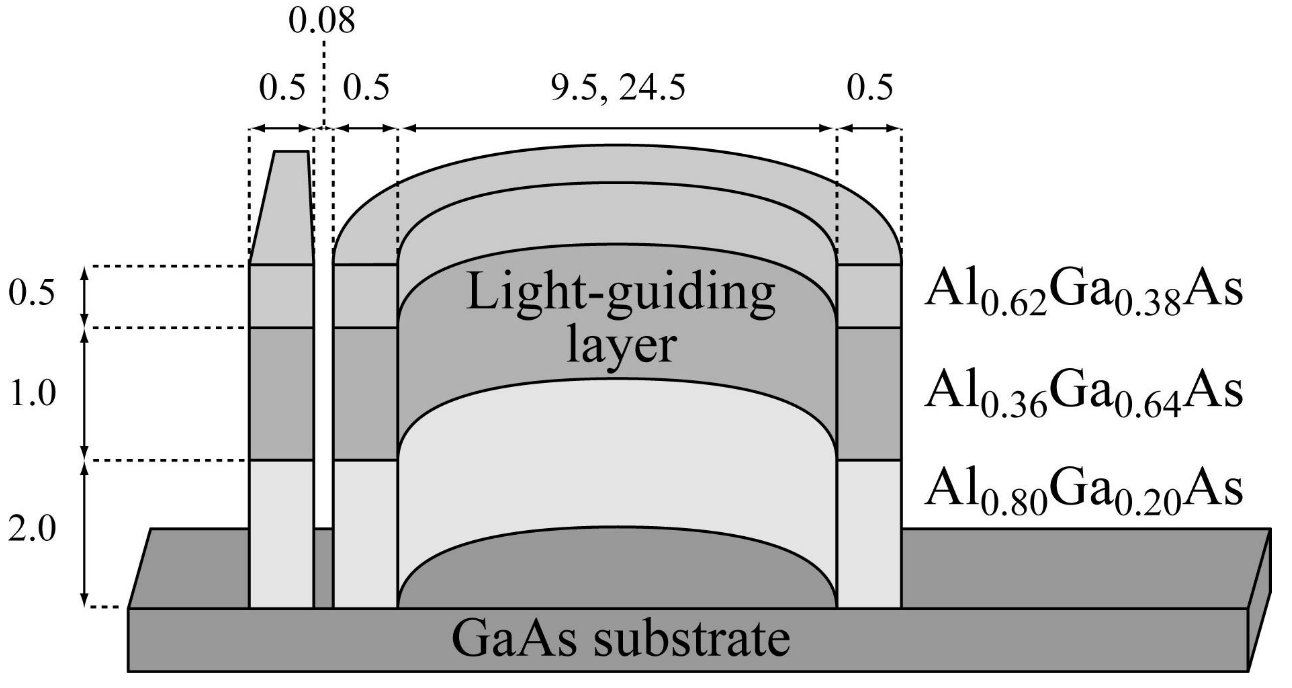






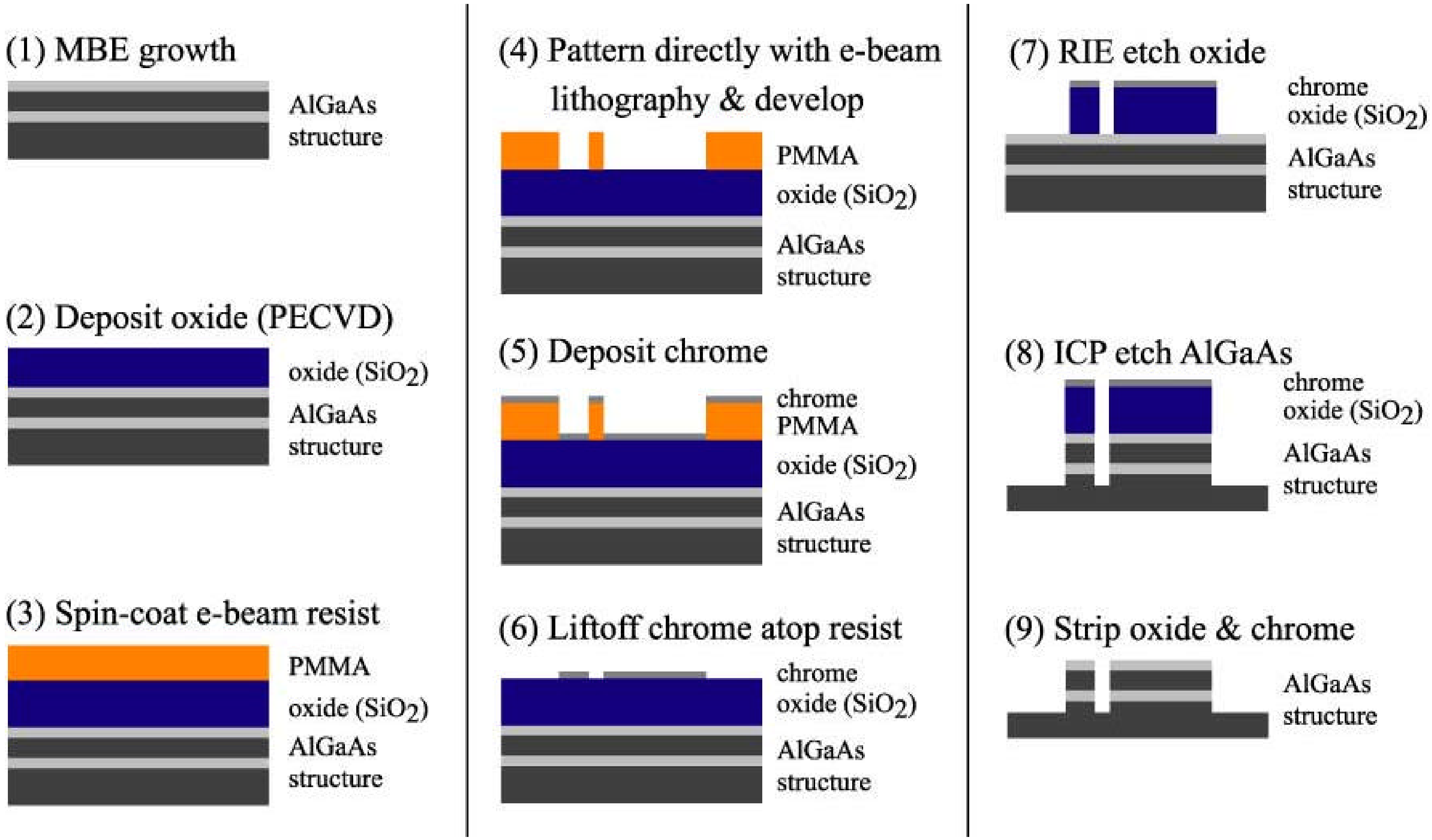
"Engineerable Photonic Media…"
J. E. Heebner, P. Chak, S. Pereira, J. E. Sipe and R. W. Boyd, JOSAB, (2004)

Lets Build ONE Resonator First!



(all dimensions in microns)

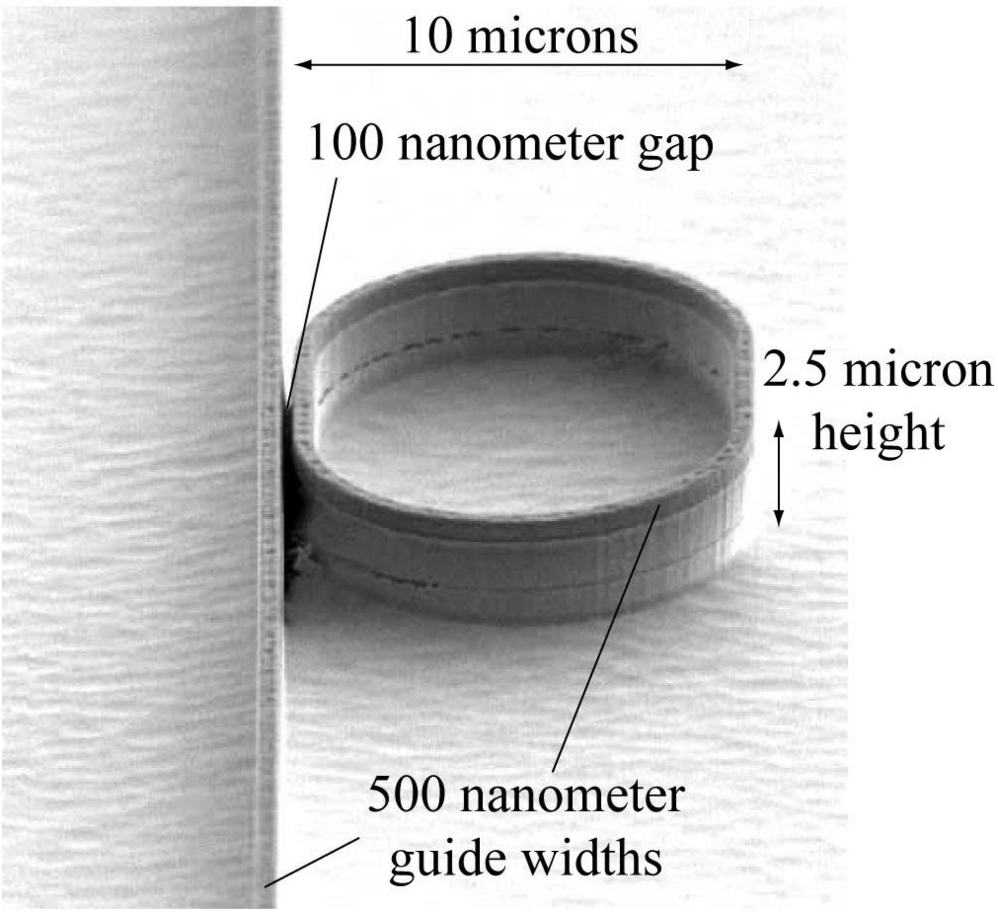
Fabrication Process



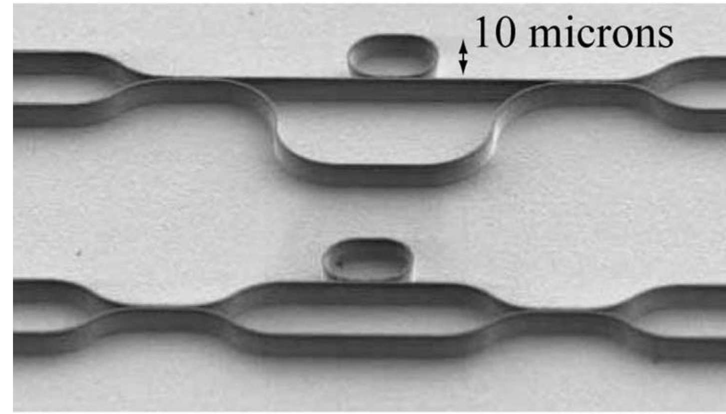
- MBE vertical growth done in Rochester by Gary Wicks
- Lateral patterning processes done at Cornell Nanofabrication Facility (CNF)
- Final etch done at Laboratory for Physical Sciences (UMD)

Fabricated Devices ($Al_{.36}Ga_{.64}As$)

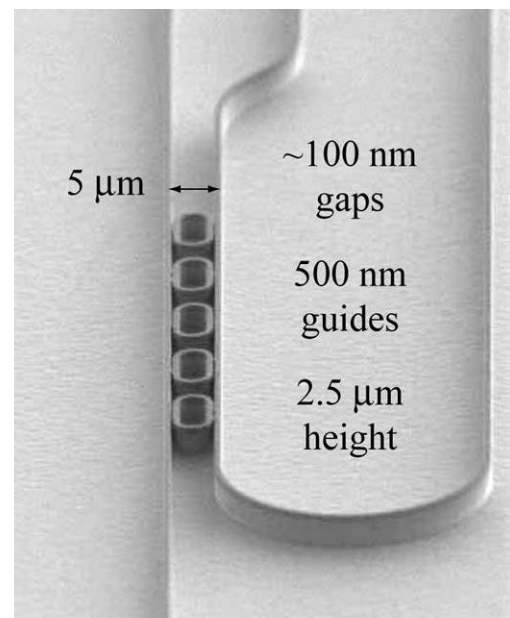
MBE grown, E-BEAM patterned, ICP etched



employed "racetracks" have extended coupling length ~ 2-4 microns

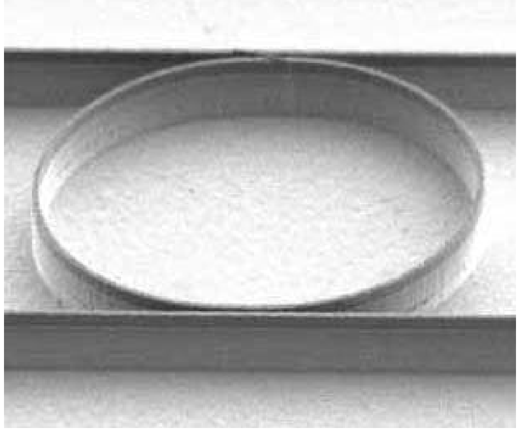


~100 nm gaps
500 nm guides
2.5 μm height

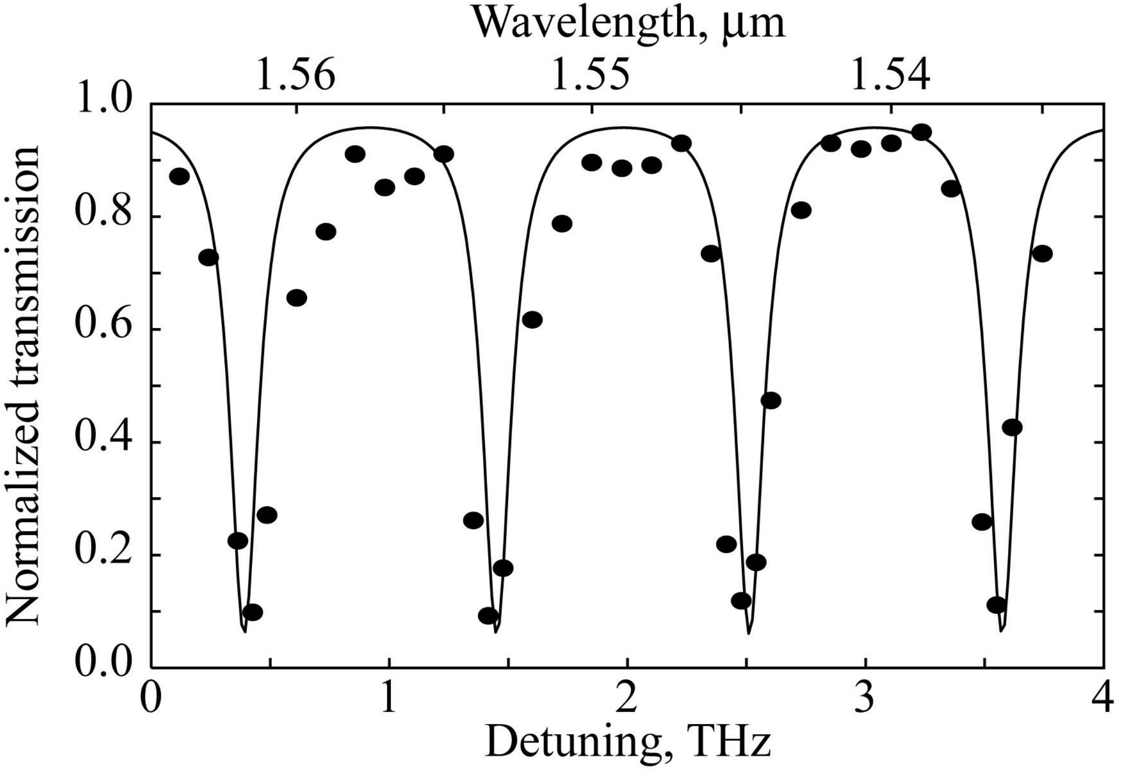


Microresonator Add-Drop Transmission

12.5 micron radius
TM excitation



FSR = 1.1 THz (8.8 nm)
BW = 110 GHz
F = 10, Q = 1750

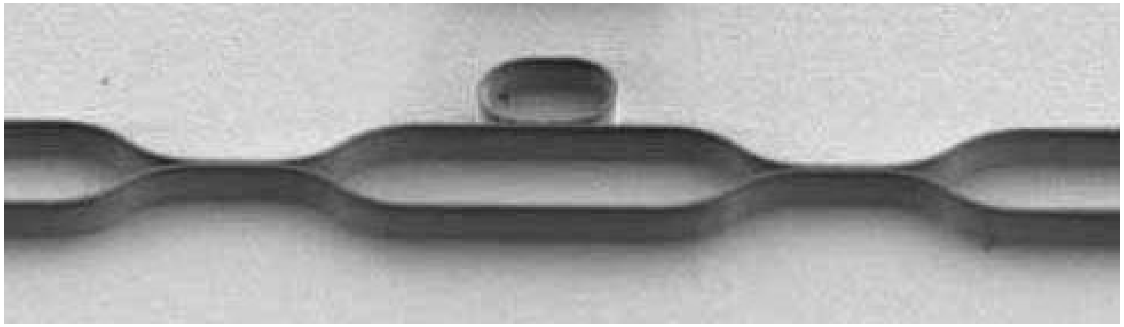


A high Q is not our goal – remember: Q<200 for 1THz bandwidth
Can do a lot with Q=200 due to quadratic scaling laws

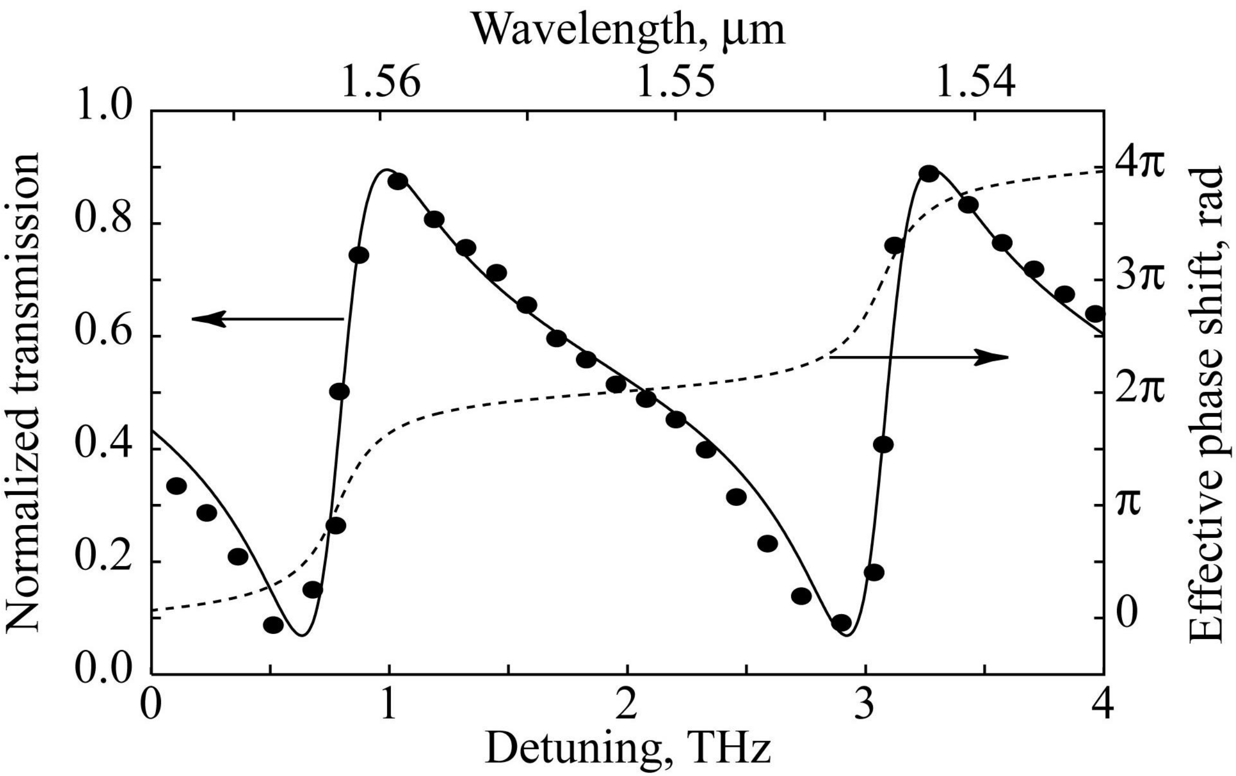
Microresonator Effective Phase Shift

(Inferred from MZI spectral interferogram)

5 micron radius
TM excitation



FSR = 2.3 THz (18.3 nm)
BW = 240 GHz
F = 10, Q = 800



Additionally,
GVD = 2 ps^2

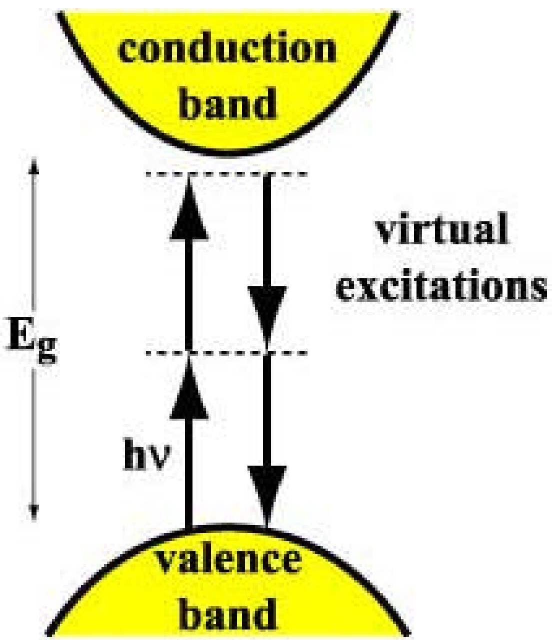
If resonators are spaced
by 20 microns:
GVD = 100 ps^2/mm

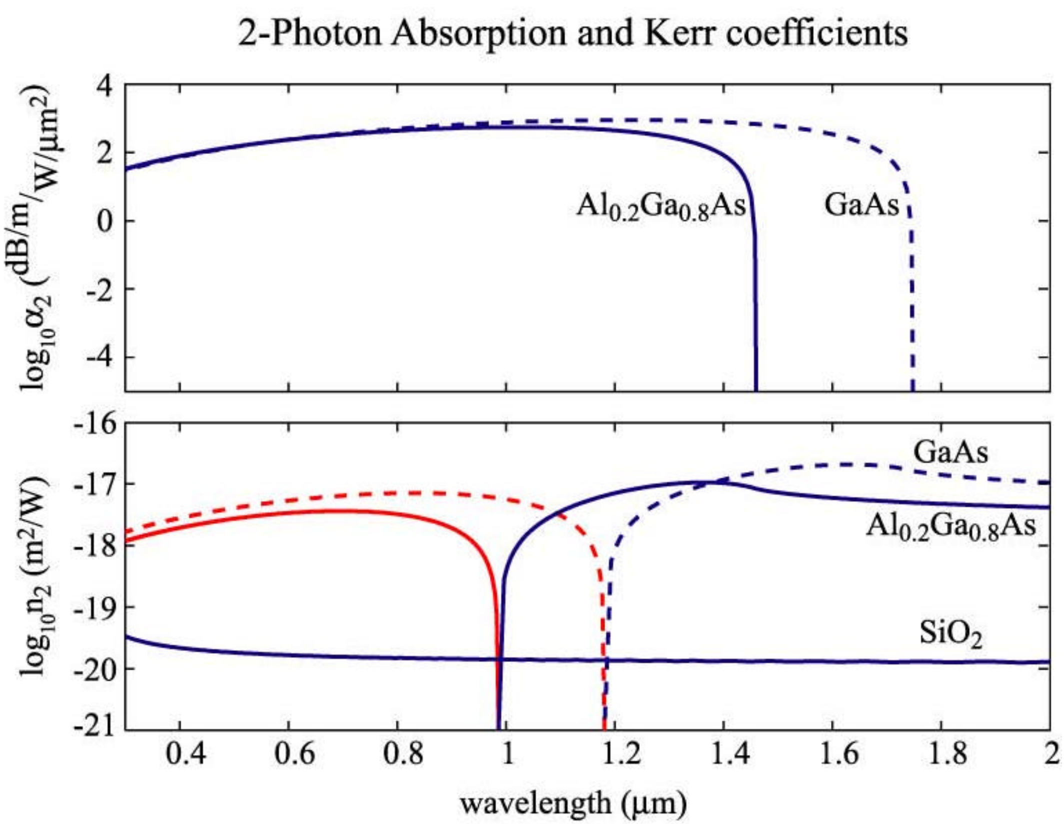
=10^{6-7} GVD silica fiber

AlGaAs Kerr Nonlinearity

- **Strong nonlinearity** – the refractive nonlinearities in semiconductors can be 2-3 orders of magnitude larger than in silica glass, due to a smaller bandgap (dependence on bandgap is to the –4 power)
- **Fast, sub-picosecond response** – If the photon energy is slightly less than the half–gap energy, two-photon absorption may be avoided, leaving a reasonably strong nonlinearity. [Sheik-Bahae, Hagan,Van Stryland]
- **Good NL figure of merit (NLFOM)** – If carrier generation via two-photon absorption is avoided, a fast (femtosecond response) bound nonlinearity remains.

  $Al_{0.2\text{-}0.4}Ga_{0.8\text{-}0.6}As$ and **chalcogenide** glasses (e.g. As_2Se_3) satisfy these requirements [Stegeman, Slusher, Wise].





π- Kerr Phase Shift from a Single Resonator?

<u>What injected power is necessary?</u>

Well, for comparison SM silica fiber requires **500 W-m**

- n_2 is higher in AlGaAs by **~100X**
- Confinement is tighter (air-cladding) by $50\mu m^2$ / $0.5\mu m^2$ **~100X**
- Resonator enhancement of **~100X**

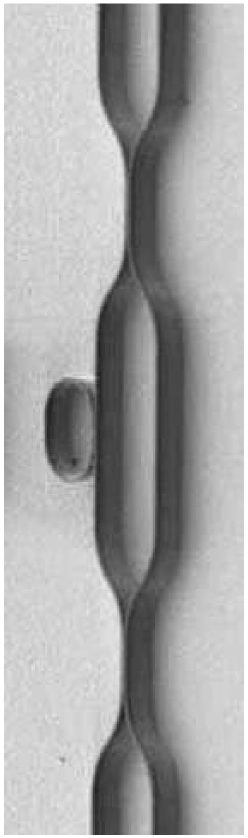
At extracted phase of π, (strongly driven) sensitivity saturates **~1/2**

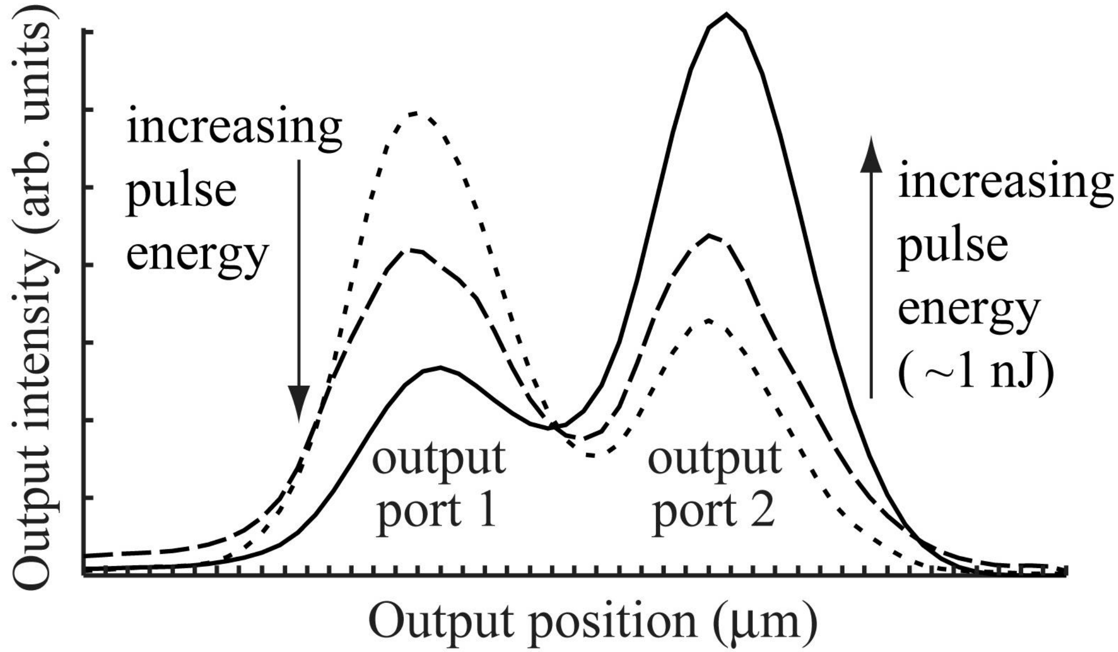
Power Threshold = 1000 W-mm / 35 mm ~ 30 W

Microresonator Nonlinear Self-Switching

implying an NL phase shift of ~ π

output imaged on camera





OPG input (10 Hz, 25ps, ~1nJ, 1.545μm)

“Enhanced Linear and Nonlinear Optical Phase Response of AlGaAs Microring Resonators”
Heebner, Lepeshkin, Schweinsberg, Wicks, Boyd, Grover, Ho, Accepted Opt. Lett, (2004).

Conclusions

- The nonlinearity and group velocity dispersion can be 6-8 orders of magnitude greater than in fiber. Pulse propagation (as in solitons) behaves similarly but evolves at the **100 micron** scale rather than the **kilometer** scale.

- A SCISSOR connects all-pass filters without feedback so phase is cumulative while **bandgaps are nonexistent** rather than complicated with transmission ripple found in other unapodized PBG media.

- **Losses** and **irreproducibilities** are still too high for microresonator arrays. Ultimately losses are of the same order as high dielectric contrast photonic crystals.
  The technical barriers to high transmission and precise fabrication in microresonator and photonic crystal systems is being overcome.

- To be feasible as elements in exotic engineerable nonlinear media, we showed that microresonators can indeed display $f_{\mathbf{NL}}$ **~** p.

Acknowledgements & Publications

Gary Wicks

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Ping Tong Ho

Richart Slusher

John Sipe

Deborah Jackson

Rebecca Welty

& others I may have forgotten!

“Enhanced Linear and Nonlinear Optical Phase Response of AlGaAs Microring Resonators”
J. E. Heebner, N. Lepeshkin, A. Schweinsberg, G. Wicks, R. W. Boyd, R. Grover, and P.-T. Ho, accepted Optics Letters, (2004)

“Optical Transmission Characteristics of Fiber Ring Resonators”
J. E. Heebner, V. Wong, A. Schweinsberg, and R. W. Boyd, accepted JQE, (2004)

“Engineerable Photonic Media: A Comparison of Microresonator-Based Waveguiding Structures for Large Scale Integration of Linear and Nonlinear Optical Devices”
J. E. Heebner, P. Chak, S. Pereira, J. E. Sipe and R. W. Boyd, submitted to JOSAB, (2004)

“Strong Dispersive and Nonlinear Optical Properties of Microresonator-Modified Optical Waveguides”
J. E. Heebner and R. W. Boyd, SPIE, 3, 4969-41, (2003)

“Slow and Fast Light in Resonator-Coupled Waveguides”
J. E. Heebner and R. W. Boyd, JMO, (2002)

“SCISSOR Solitons & Other Propagation Effects in Microresonator-Modified Waveguides”
J. E. Heebner, R. W. Boyd, and Q. Park, JOSA B, 19 (2002)

“Slow Light, Induced Dispersion, Enhanced Nonlinearity, and Optical Solitons in a Resonator-Array Waveguide”
J. E. Heebner, R. W. Boyd, and Q. Park, Phys. Rev. E, 65 (2002)

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S. Pereira, J. E. Sipe, J. E. Heebner, and R. W. Boyd, Optics Letters, 27 (2002)

“Beyond the Absorption-Limited Nonlinear Phase Shift with Microring Resonators”
S. Blair, J. E. Heebner, and R. W. Boyd, Optics Letters, 27 (2002)

“Sensitive Disk Resonator Photonic Biosensor”
R. W. Boyd and J. E. Heebner, Applied Optics, 40, pp. 5742-5747, (2001)

“Enhanced All-Optical Switching Using a Nonlinear Fiber Ring Resonator”
J. E. Heebner and R. W. Boyd, Optics Letters, 24, pp.847-849, (1999)