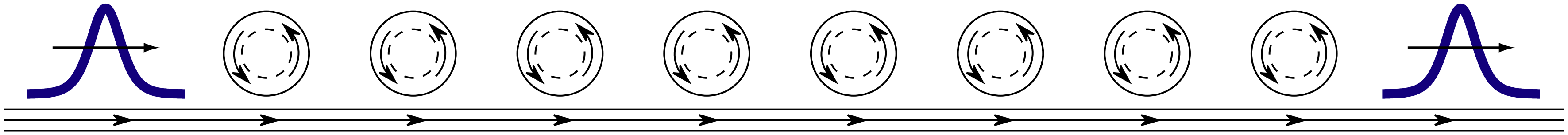
Running with SCISSORS:

Slow Light, Induced Dispersion, Enhanced Nonlinearity, Self-Steepening, and oh yes... a new type of SOLITON!



(SCISSOR = Side-Coupled Integrated Spaced Sequence Of Resonators)

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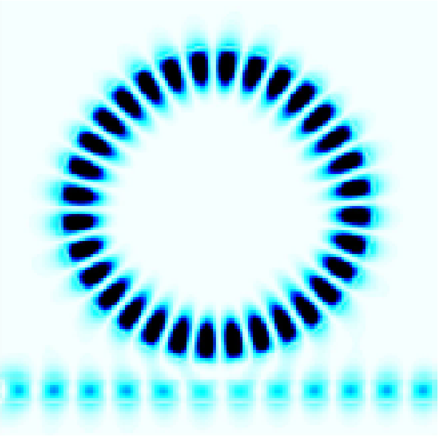
Motivation

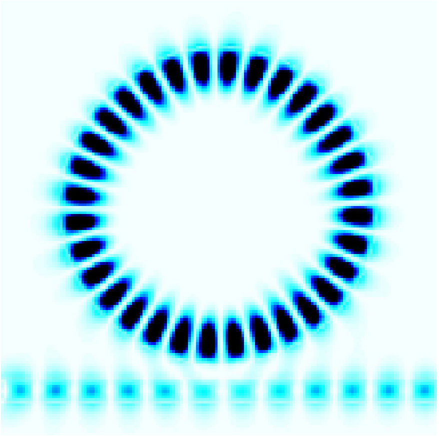
To exploit the ability of microresonators to enhance nonlinearities and induce strong dispersive effects to create structured waveguides with exotic properties.

Currently, most of the work done in microresonators involves applications 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:

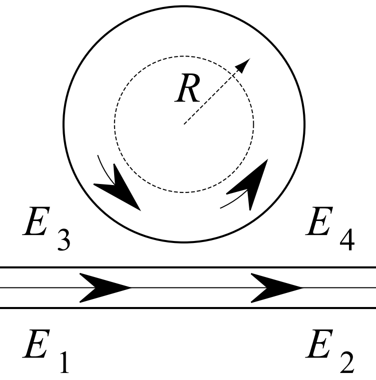


- slow light propagation
- induced dispersion
- enhanced nonlinearities



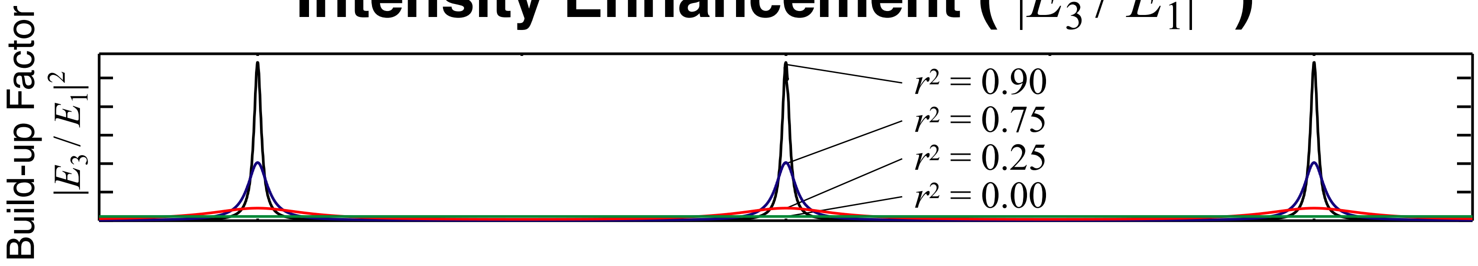
Basics for a Single Microresonator

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

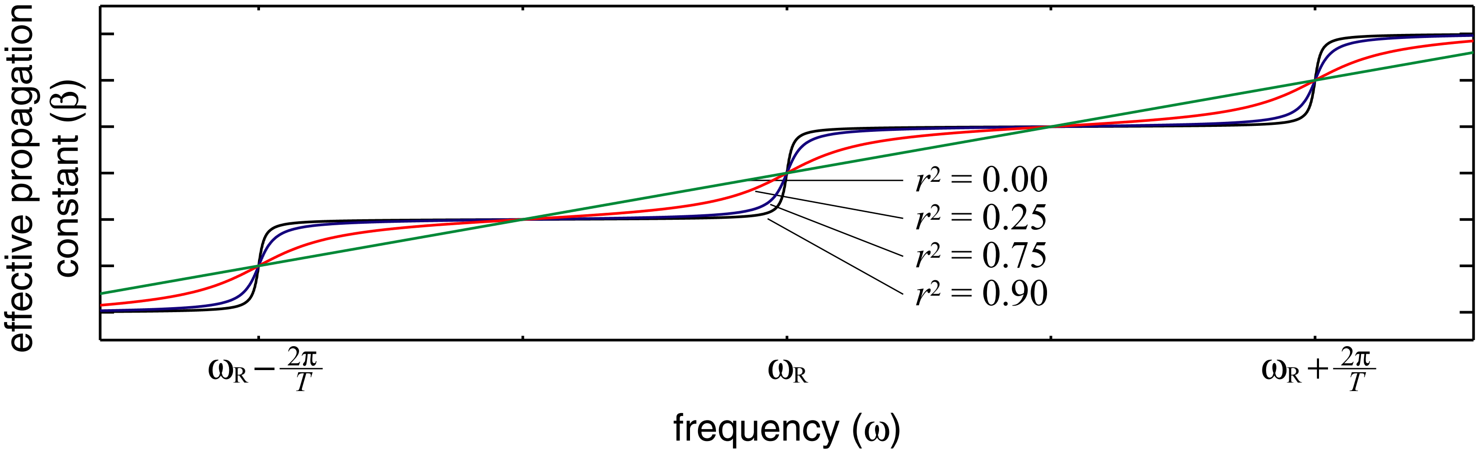


$$\begin{pmatrix} E_4 \\ E_2 \end{pmatrix} = \begin{pmatrix} r & it \\ it & r \end{pmatrix} \begin{pmatrix} E_3 \\ E_1 \end{pmatrix}$$

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



Modified Dispersion Relation (β vs. ω)



Definitions

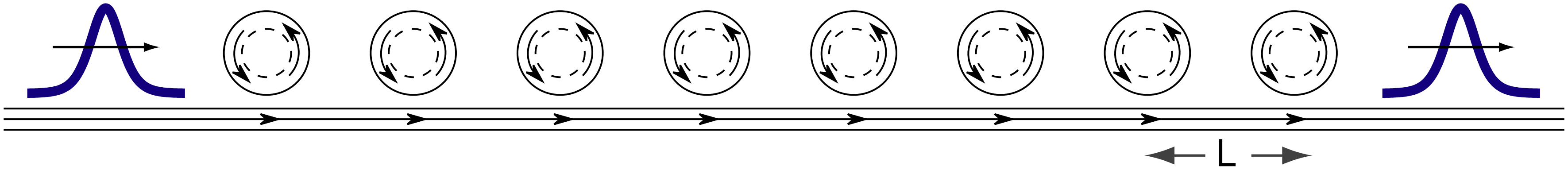
Finesse

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

Transit Time

$$T = \frac{n2\pi R}{c}$$

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 NO photonic bandgap is in effect to create the enhancements. Feedback is intra-resonator and not inter-resonator.

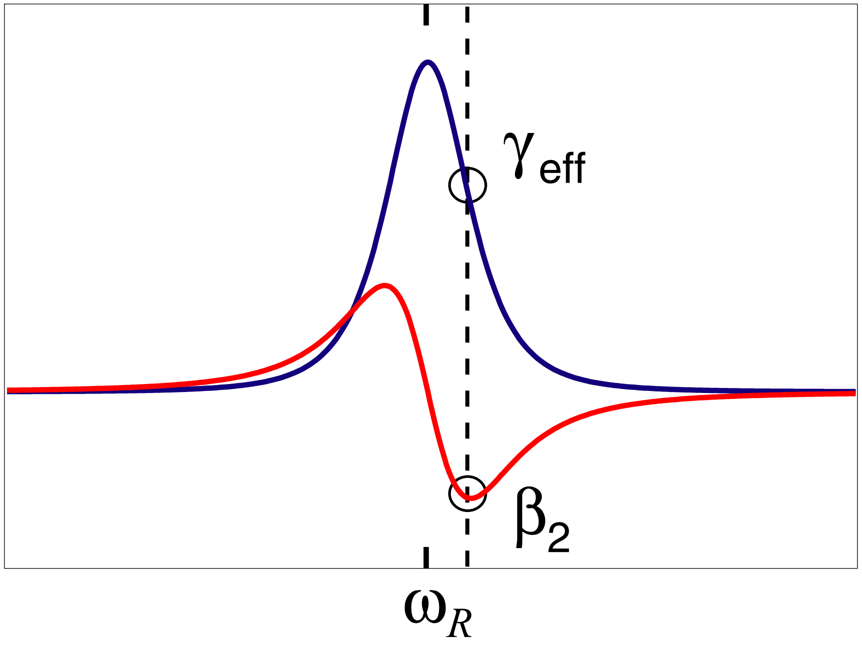
Nonlinear Schrödinger Equation (NLSE)

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

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

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

adjustable by controlling ratio of
transit time to pulse width

Resonator induced dispersion can be 5-7 orders of magnitude greater than material dispersion in 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

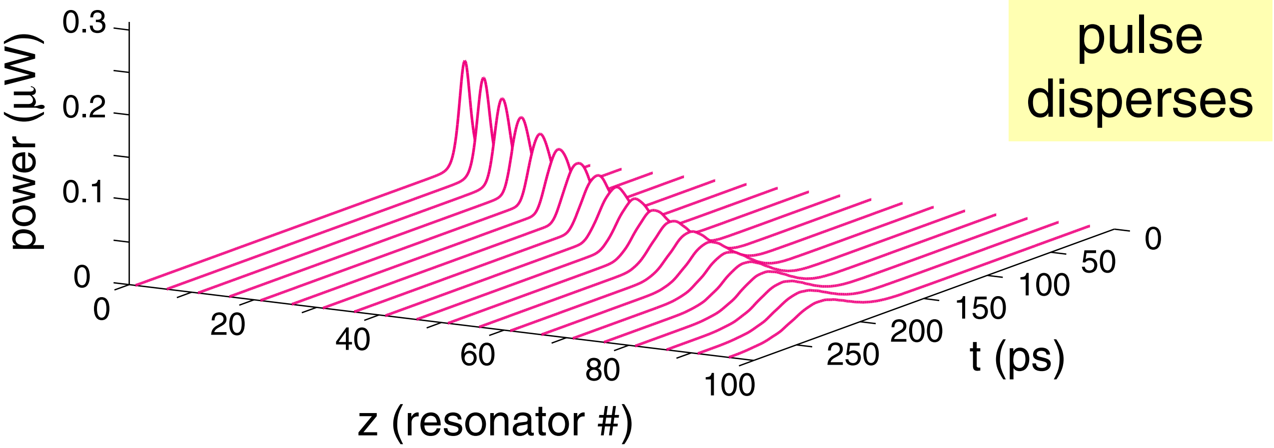
5 μm diameter resonators with a finesse of 30

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

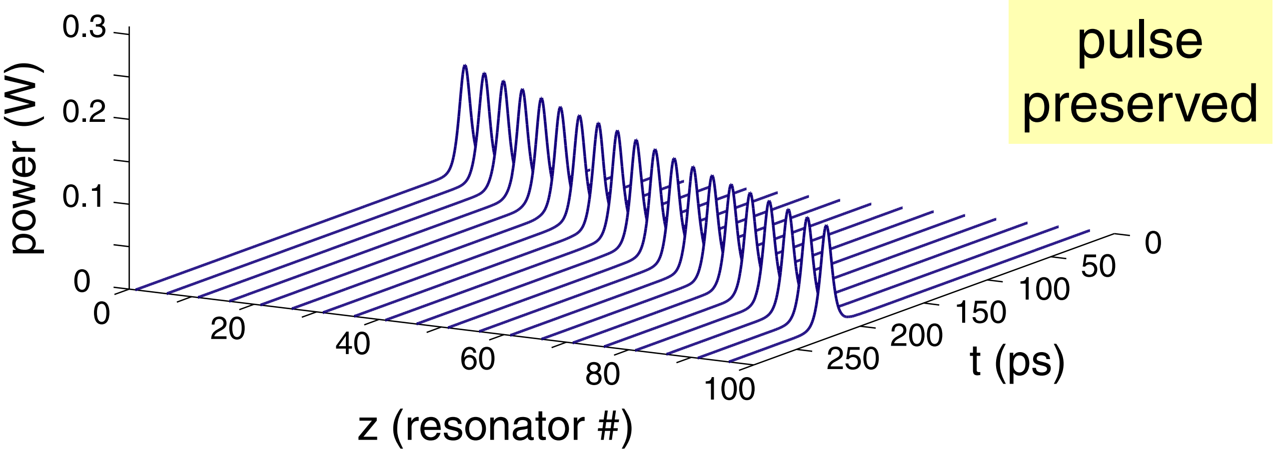
simulation assumes a chalcogenide/GaAs-like nonlinearity

Weak Pulse



pulse disperses

Fundamental Soliton



pulse preserved

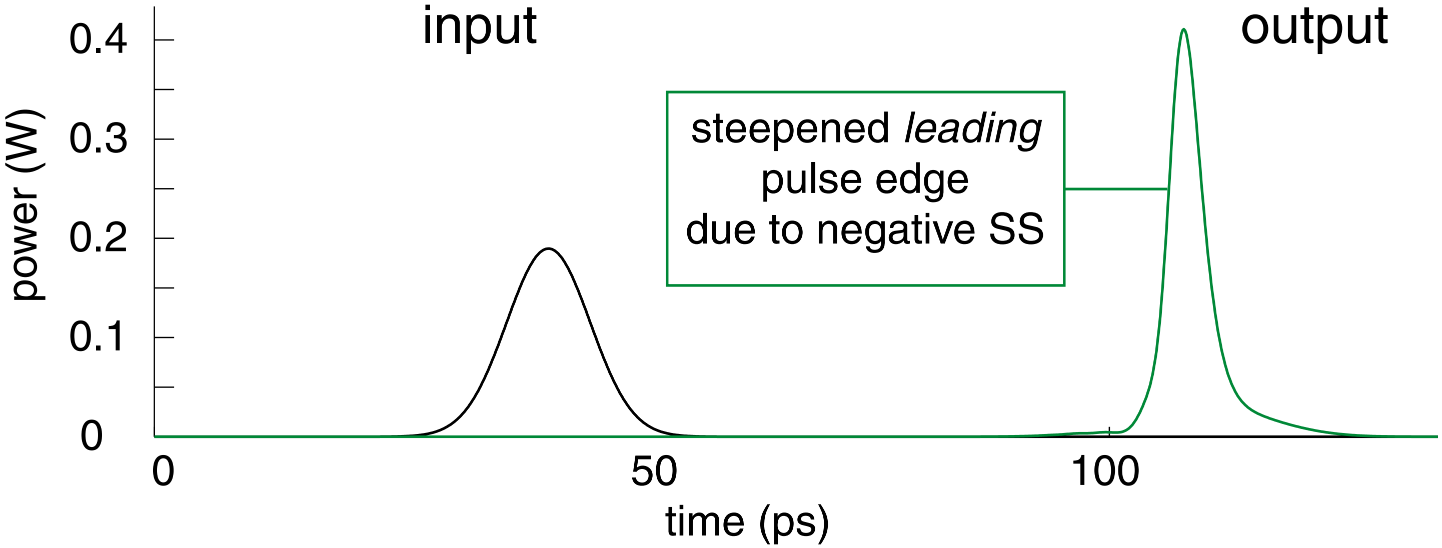
Higher-Order Effects - Self-Steepening

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:

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

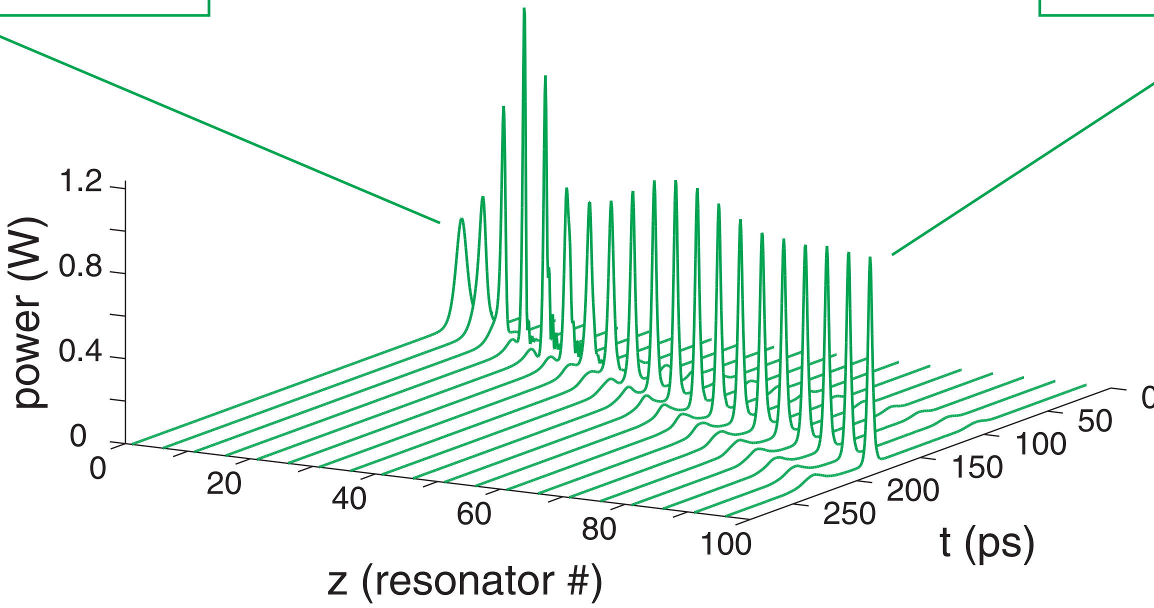
Self-steepening of a 20 ps Gaussian pulse after 100 resonators



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 2nd - order "breathing" soliton splits into 2 fundamental solitons:



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

Notice that one is compressed and uncorrupted by a pedestal.

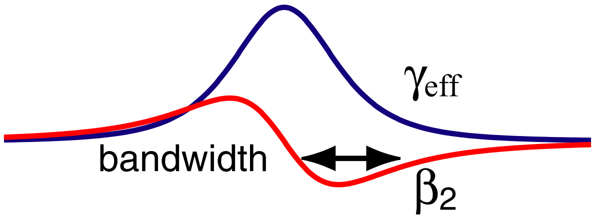
Limitations

Bandwidth

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

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 μm

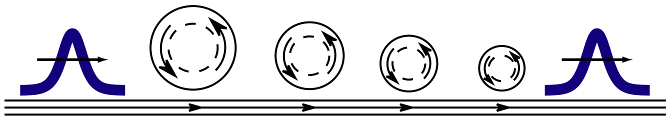
variance in gap spacing analogous to hyperfine distribution

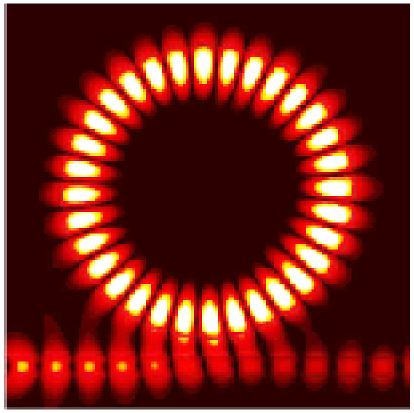
variance in radius/index analogous to Doppler broadening

Attenuation - dominated by scattering losses

may be counterbalanced by:

1) gain
2) dispersion decreasing SCISSOR :





FDTD simulations used to model scattering losses

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 in industry as all-pass filters and tunable dispersion compensators.

SCISSORs have the potential to compact soliton propagation effects down to 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 single photon)
- Slow light propagation (group-matched acousto-optics)
- EO,TO - Tunable NLSE propagation (A theorist's dream)
- Just about any other generalized NLSE effect