Laser and Parametric Optical Frequency Combs

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Outline

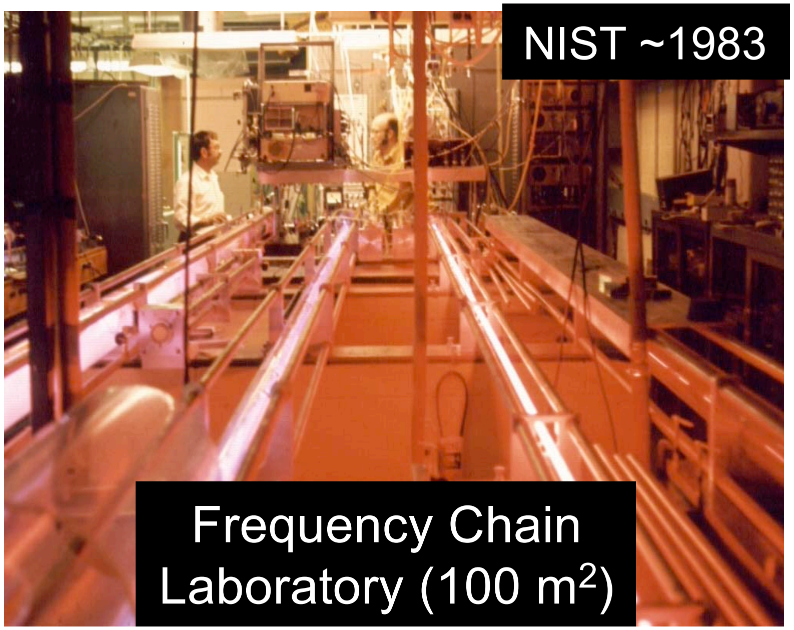
1. Background: Clocks and Precise Timing

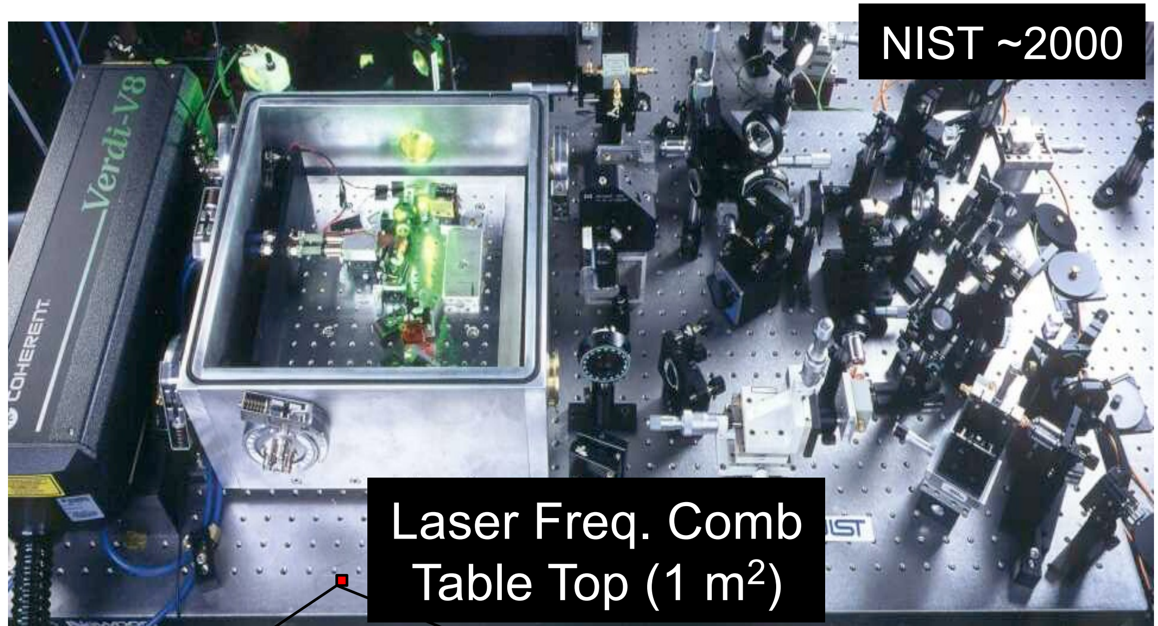
2. Counting Cycles of Light
   - The optical frequency comb

3. From Lab Scale to Chip Scale
   - Can we make a frequency comb on a chip?

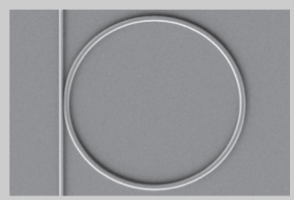
4. Applications and opportunities for frequency combs

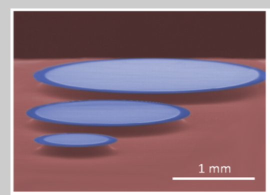
Moving from Lab Scale to Chip Scale



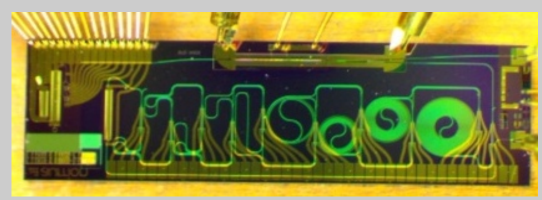


~10^4 size reduction





~1 cm^2



Future: Photonic Integrated Circuits

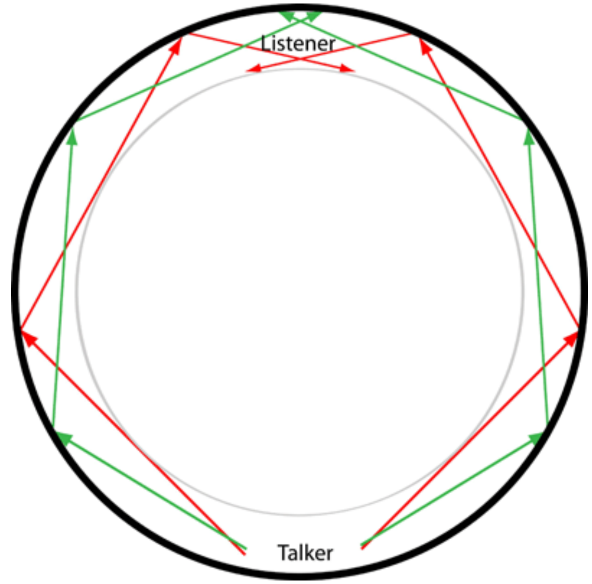
Potential Impact:

- Operation in any environment
- Chip scale clocks
- Inexpensive and mass produced
- Communication and navigation
- Sensing (environment, medical, manufacturing...)

The Whispering Gallery

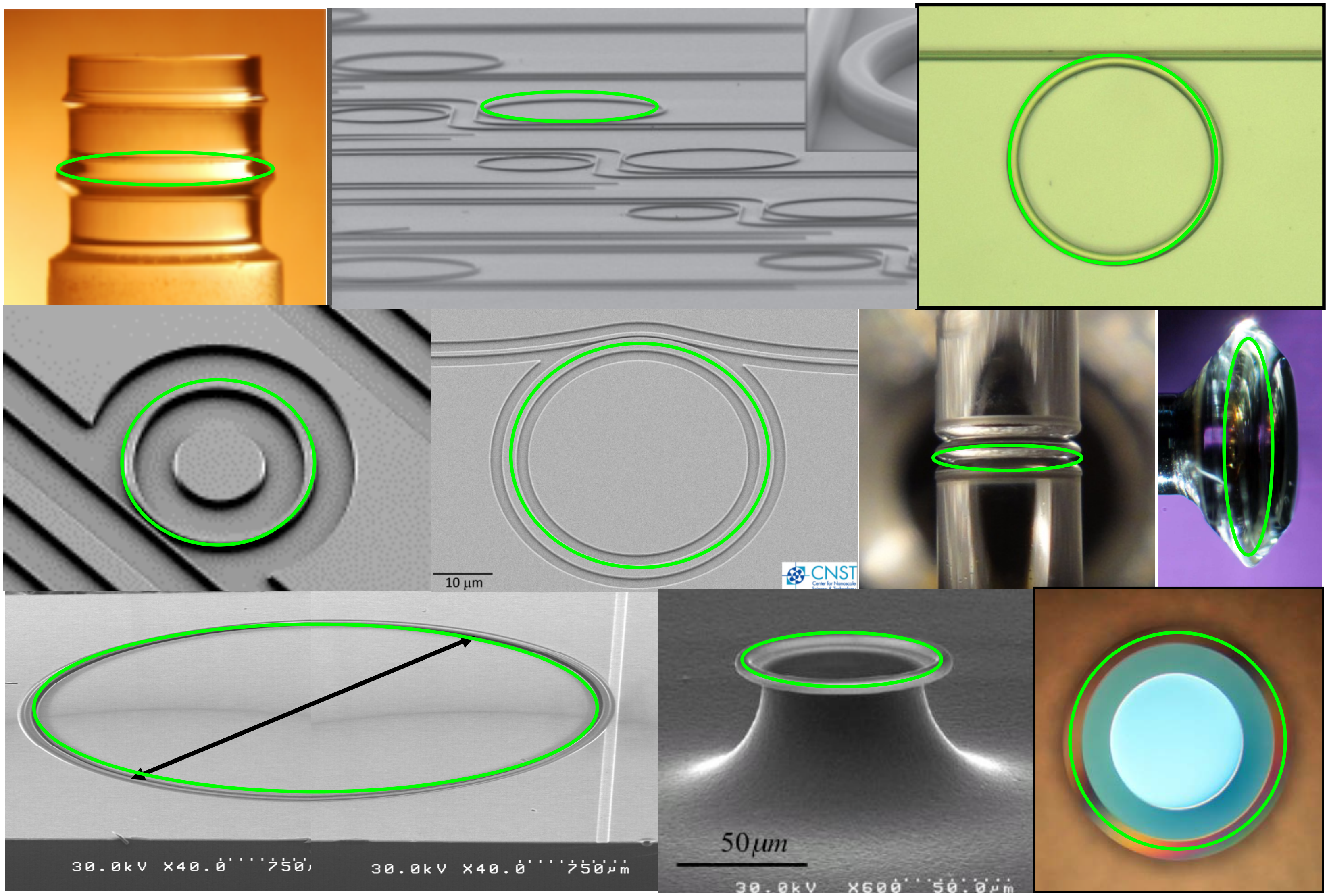
St. Paul's Cathedral (London)

Sound waves travel along circular walls by continuous reflection



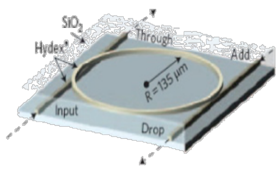
Rayleigh, L. "*The problem of the whispering gallery*" Scientific Papers, **5**, 617, 1912

Whispering Gallery Microresonators



Microresonator Gallery

Hydex

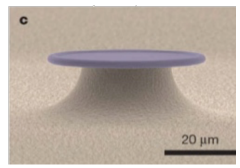


RMIT

Si:Nitride

Cornell, Purdue, NIST G-burg, EPFL, UCLA

Silica toroid

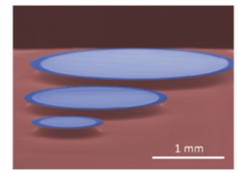


MPQ, EPFL, Caltech

Crystals

OEWaves JPL EPFL

Silica wedge

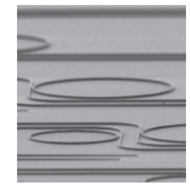


Caltech

Quartz

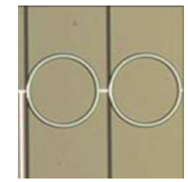
NIST

Diamond



Harvard

Al:Nitride



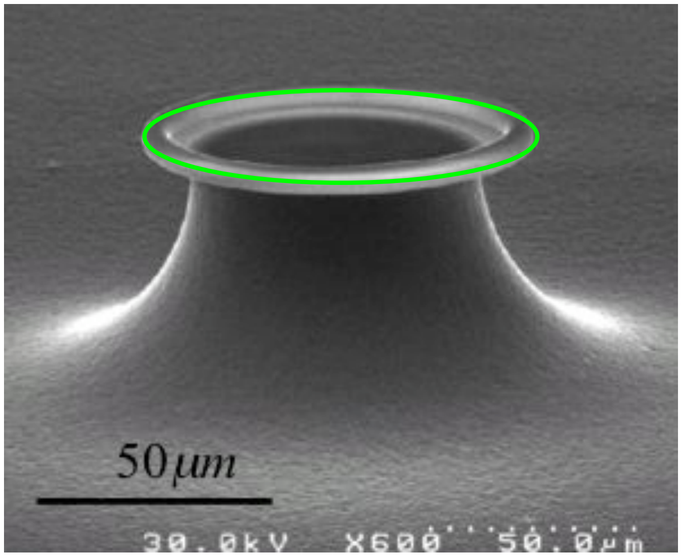
Yale

Key Properties

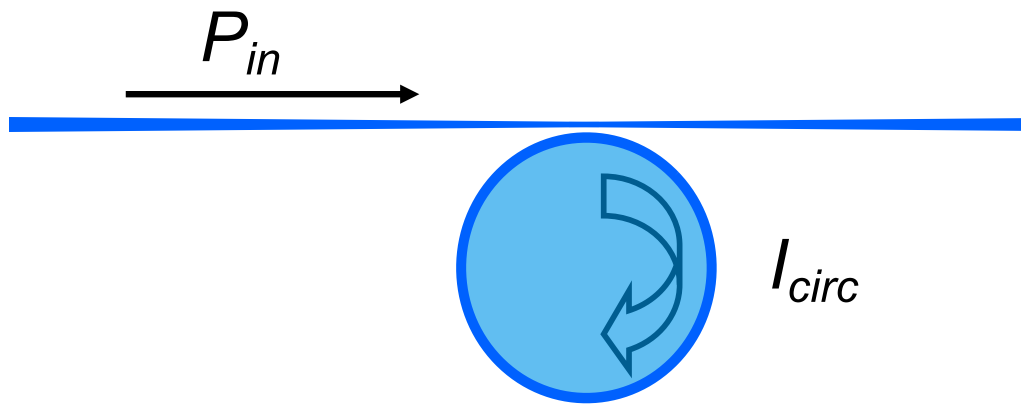
- High-Q cavity (>10^9)
- Small mode volume
- Mode-spacing given by perimeter
- Low & controllable dispersion
- Integrated chip-scale package

[1] L. Razzari, D. Duchesne, M. Ferrera, R. Morandotti, S. Chu, B. E. Little & D. J. Moss (Nature Photonics **4**, 41 – 45, 2010)
[2] J.S. Levy, A. Gondarenko, M.A. Foster, A.C. Turner-Foster, A.L. Gaeta & M. Lipson (Nature Photonics **4**, 37 – 40, 2010)
[3] P. Del'Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, T. J. Kippenberg (Nature **450**, 1214-1217, 2007)
[4] A.A. Savchenkov, A.B. Matsko, V.S. Ilchenko, I.Solomatine, D. Seidel, and L. Maleki (Phys Rev Let. **101**, 093902, 2008)
[5] S.B. Papp and S.A. Diddams (PRA **84**, 053833, 2011)
[5] F. Ferdous, H. Miao, D. E. Leaird, K. Srinivasan, J. Wang, L. Chen, L. T. Varghese & A. M. Weiner (Nature Photonics **5**, 770, 2011)

Nonlinear Optics at mW Powers



Vahala group



$$I_{circ} \approx \frac{Q}{V}\frac{c}{\omega}P_{in}$$

V = 500 μm^3 (50 μm dia. microtoroid)

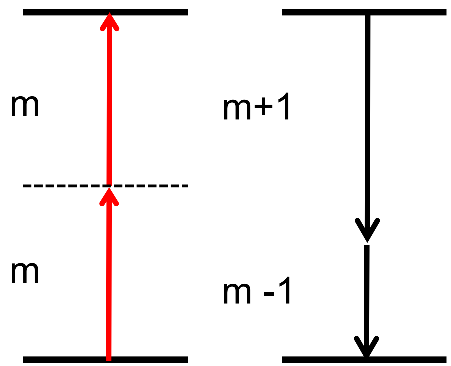
Q = 10^8

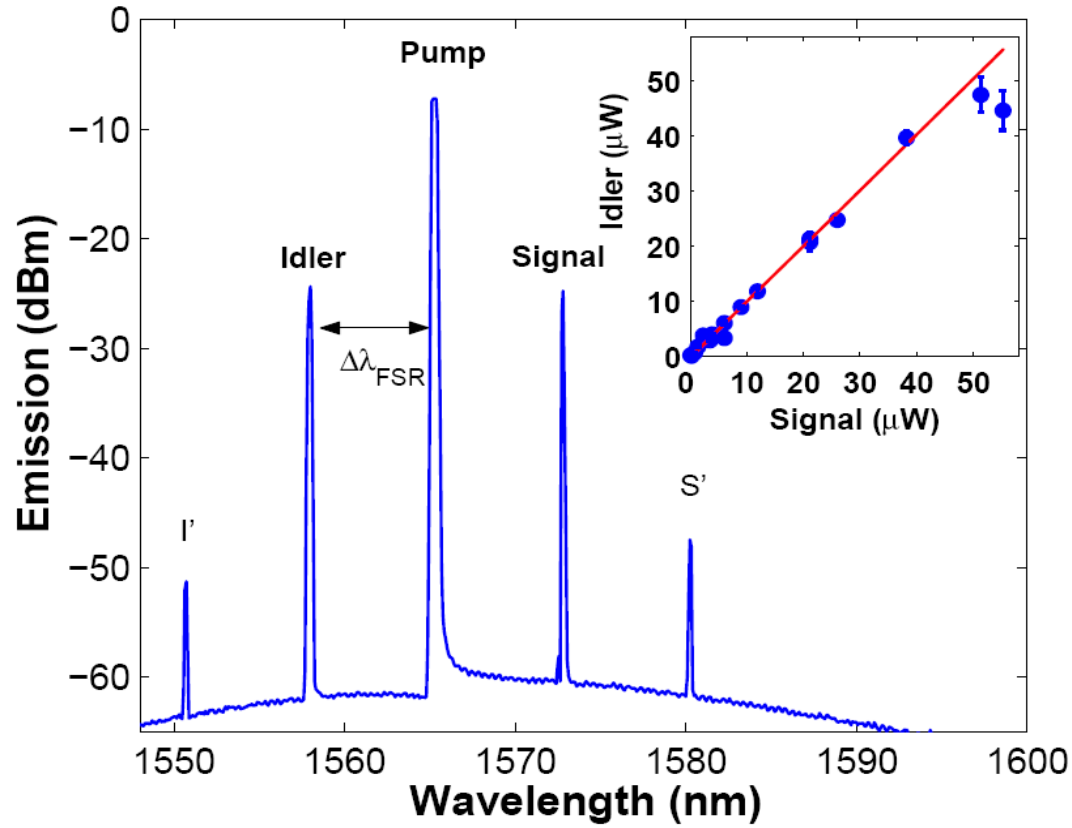
I_{circ} = 3 GWatts/cm^2 (1 mWatt input)

NIST

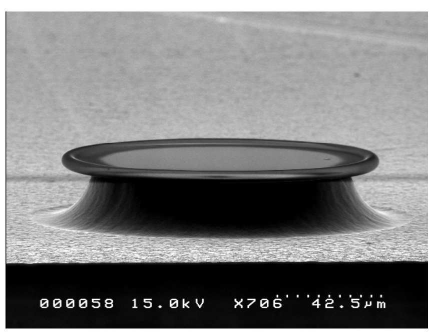
Parametric Oscillation

Two “pump” photons scattering to produce two photons at higher and lower frequency relative to pump.





Kippenberg, Spillane, Vahala, *Physical Review Letters*, August (2004).



Savchenkov, Matsko, Strekalov, Mohageg, Ilchenko, Maleki, *Physical Review Letters*, December (2004).

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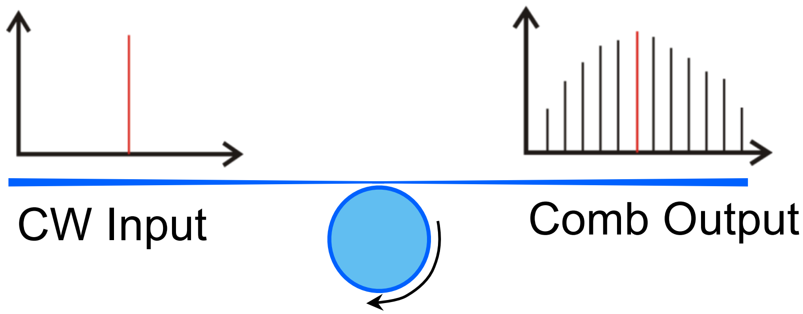
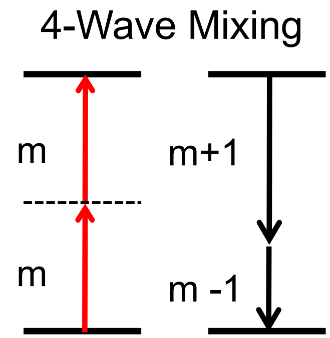
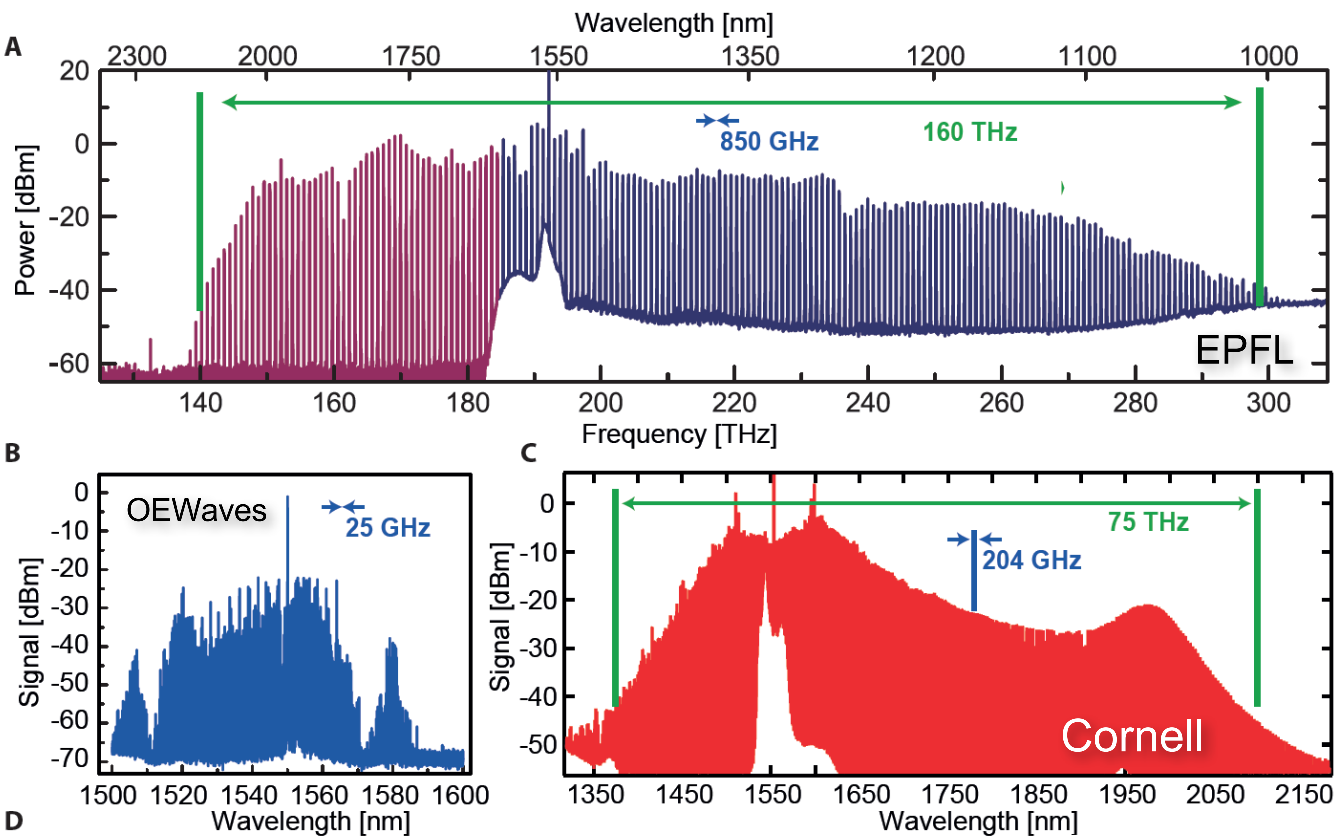
A Tiny Revolution in Frequency Combs





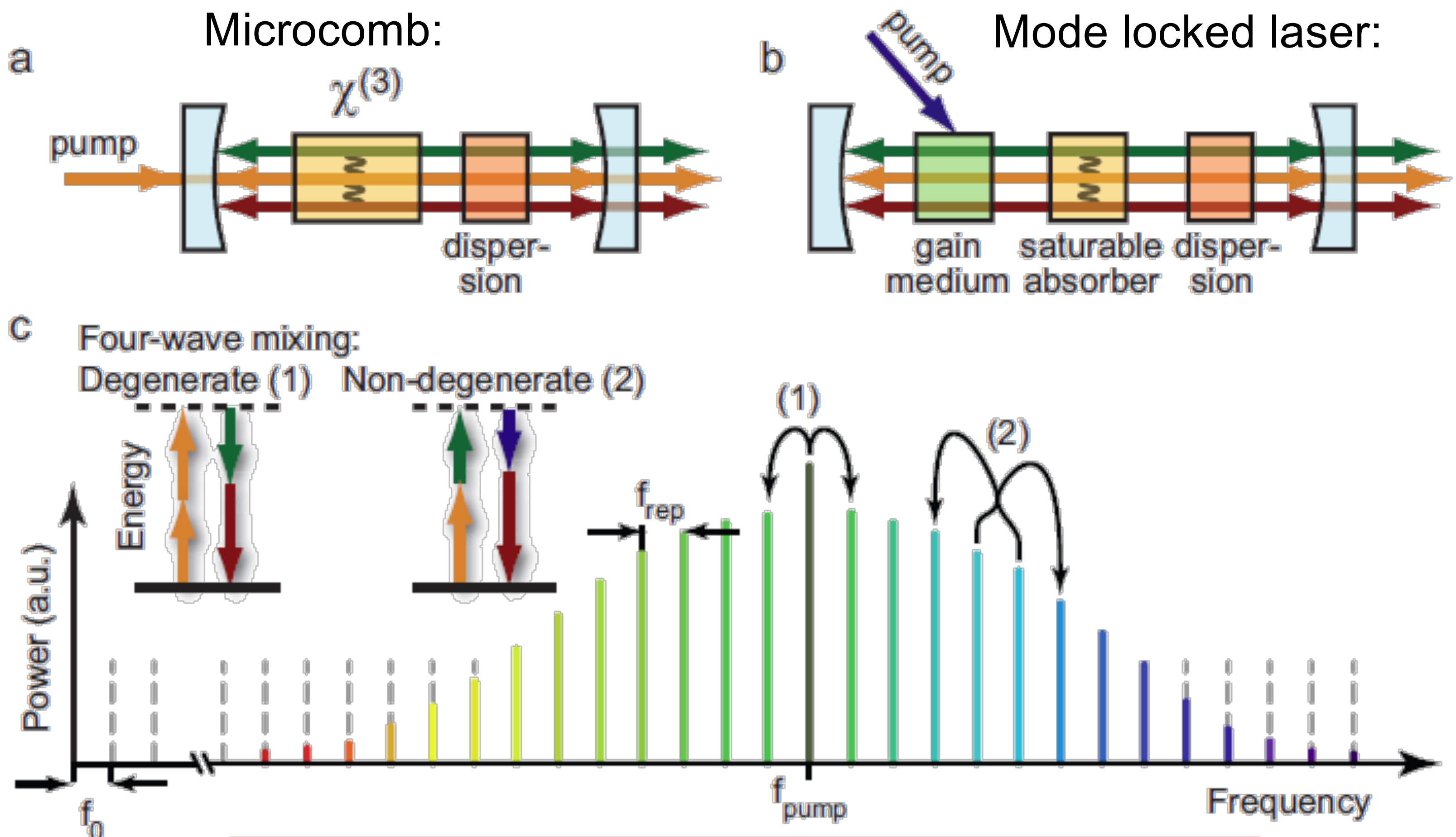
1. Energy conservation:
   $2\omega_P = \omega_S + \omega_I$
2. Momentum conservation: linear + nonlinear
3. Line spacing given by resonator size



- Combs that appear regularly-spaced are possible, but not all are useful for metrology
- Understanding (controlling?) noise processes is critical
- What is happening in the time domain?

Del'Haye, et al., Nature **450**, 1214 (2007)
Kippenberg, Holzwarth, Diddams Science **332** , 555 (2011).

Comb Generation Principle



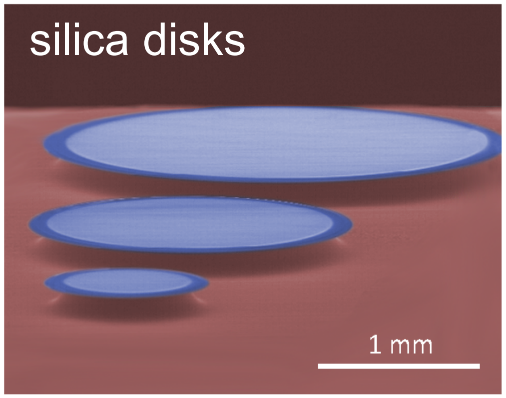
Microcomb:

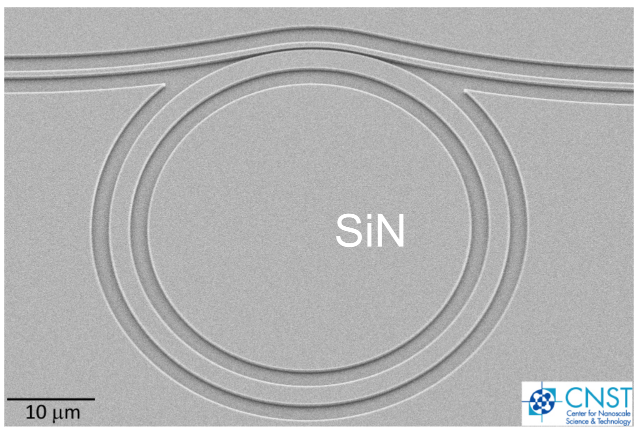
- Parametric gain vs. stimulated emission
- Pump laser part of comb (offset tuning)
- No saturable absorber

Microresonator Research at NIST

See the video on YouTube "Laser comb in a minute"
S. Papp, PRX (2013), P. Del'Haye, Appl. Phys. Lett. (2013)
F. Ferdous, Nat. Photon. (2011)
H. Lee, Nat. Photon. (2012), H. Lee Nat. Comm. (2013)

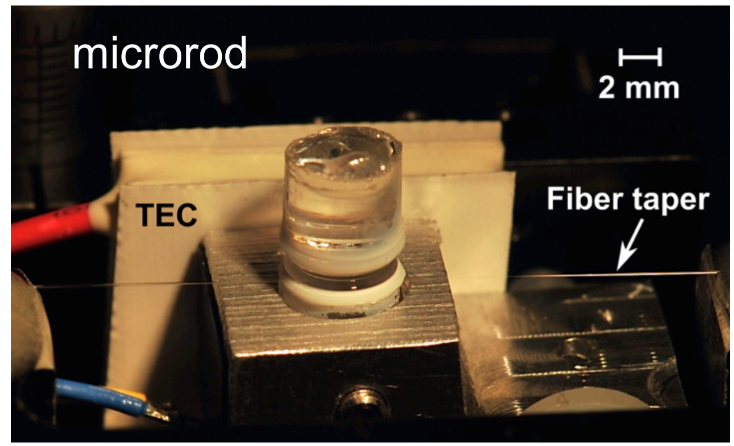
Microresonators for Comb Generation

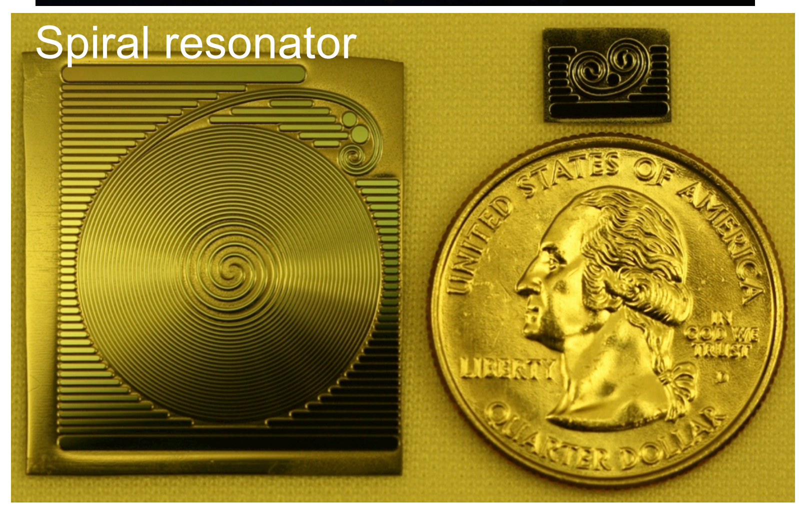




→ Q ~ 10^6 – 10^9
→ Large mode volume for low noise
→ Small mode volume for efficient nonlinear optics

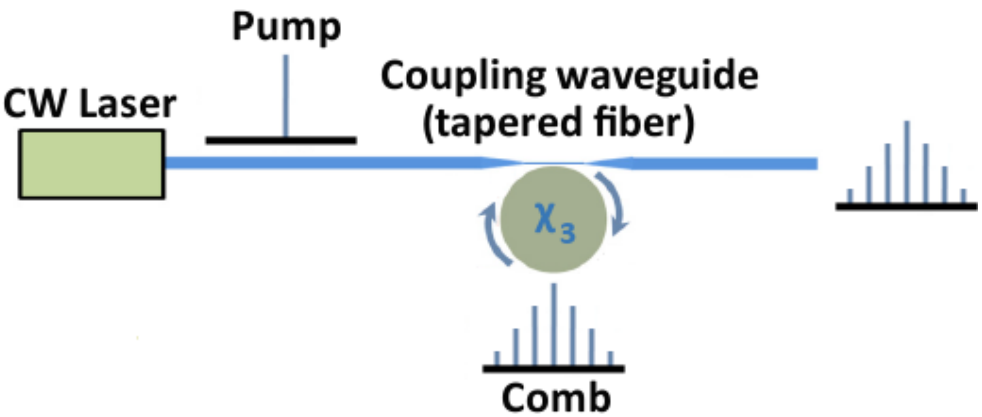
Microresonators for SBS and Laser Stabilization



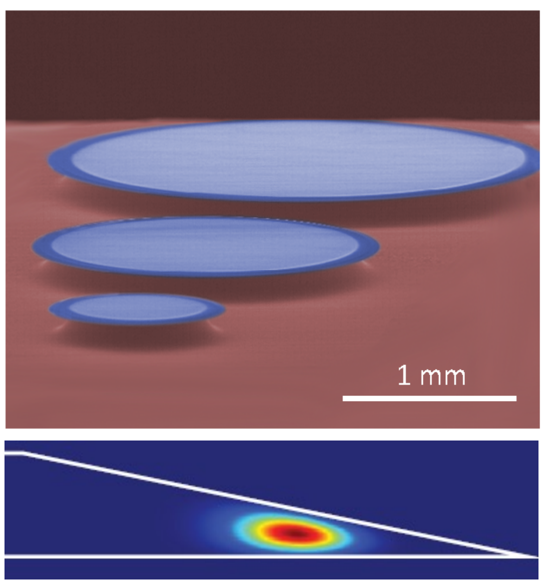


Devices: Vahala (Caltech), Srinivasan (NIST)

Kerr microcomb hardware

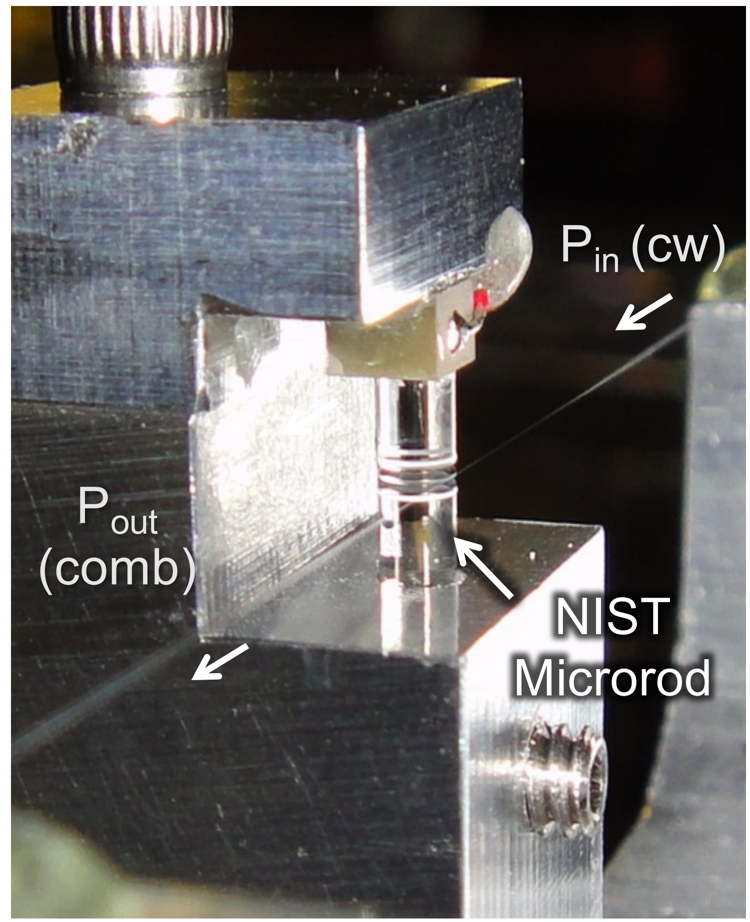


Caltech Disk Resonators



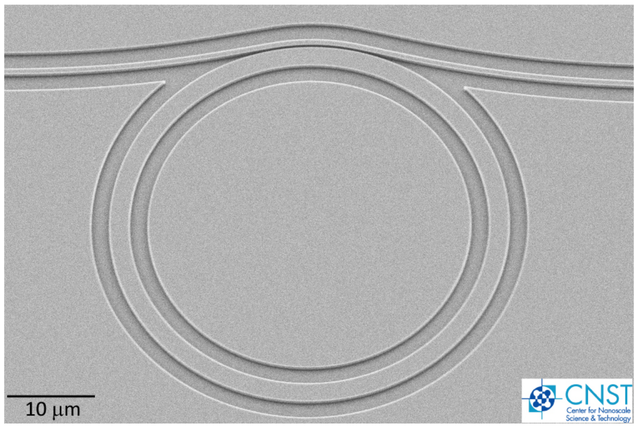
"Whispering gallery" mode

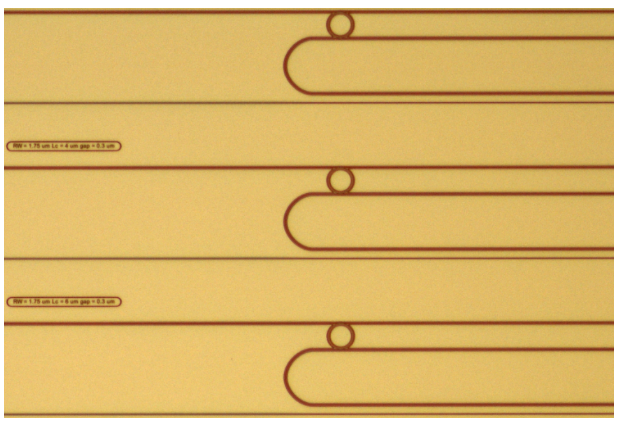
Tapered Fiber Coupling

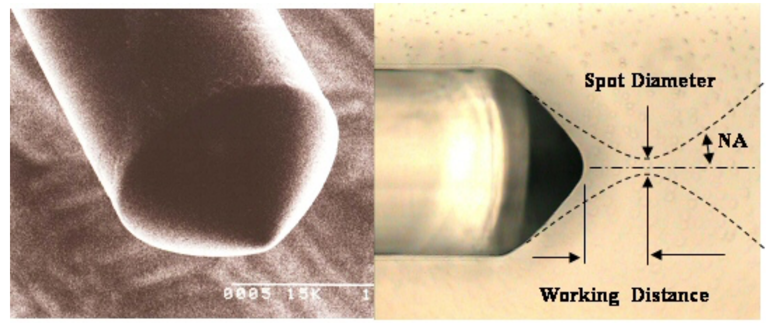


Kerr microcomb hardware

Si_3N_4 + lensed fibers

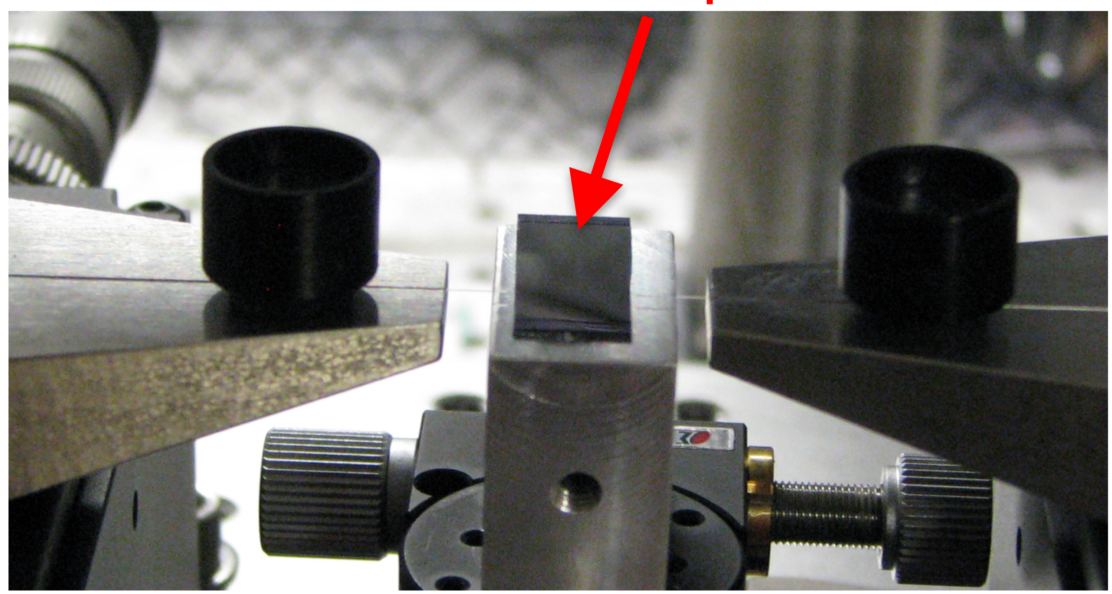






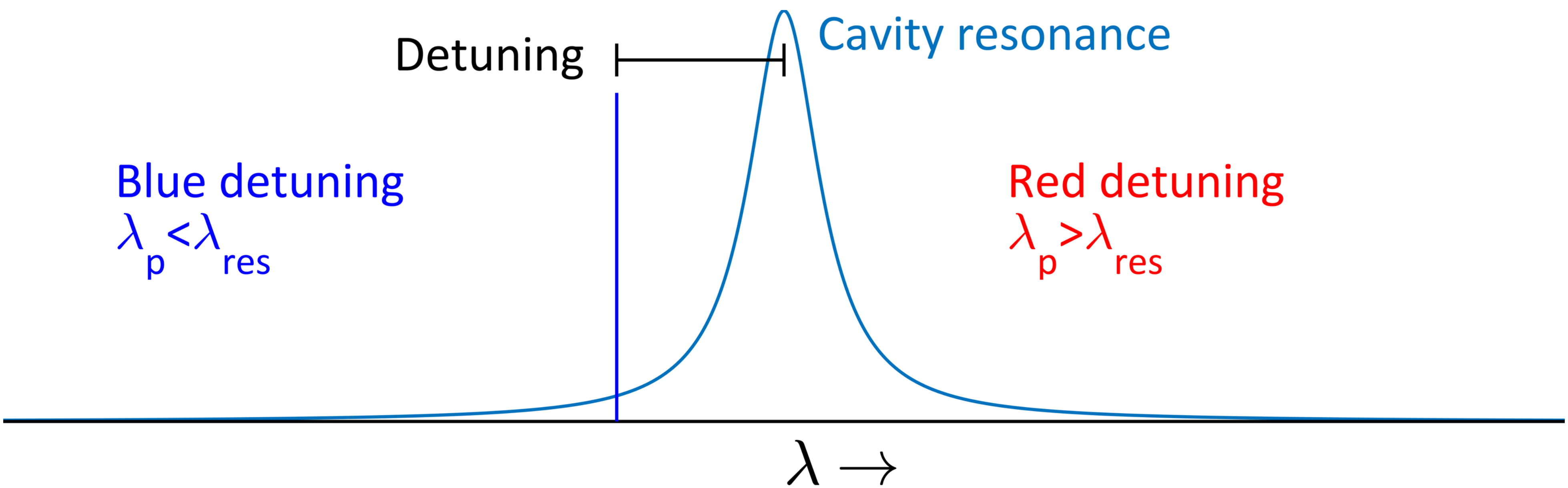
Moritex.com

Chip



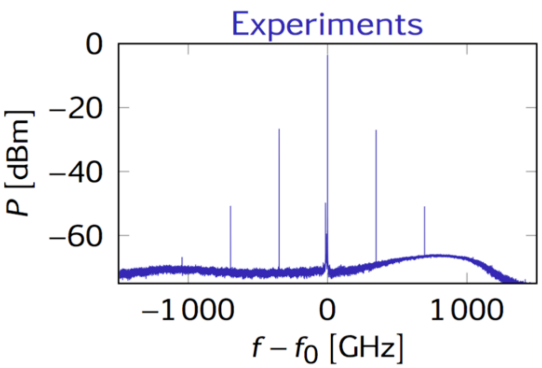
Microcomb Initiation

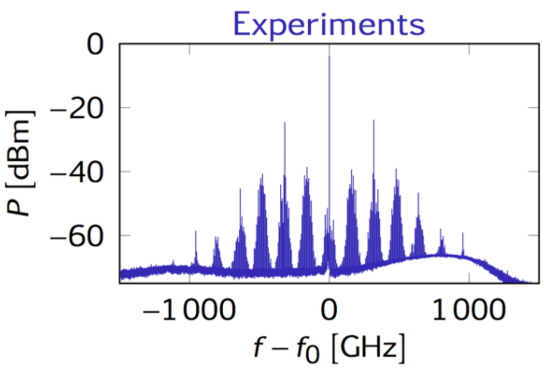
→ Initiate Kerr comb by tuning frequency of CW pump laser into a resonance of the microresonator

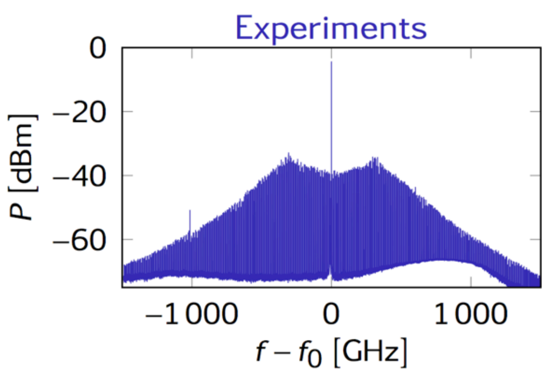


Kerr Nonlinear Microcavity Resonance

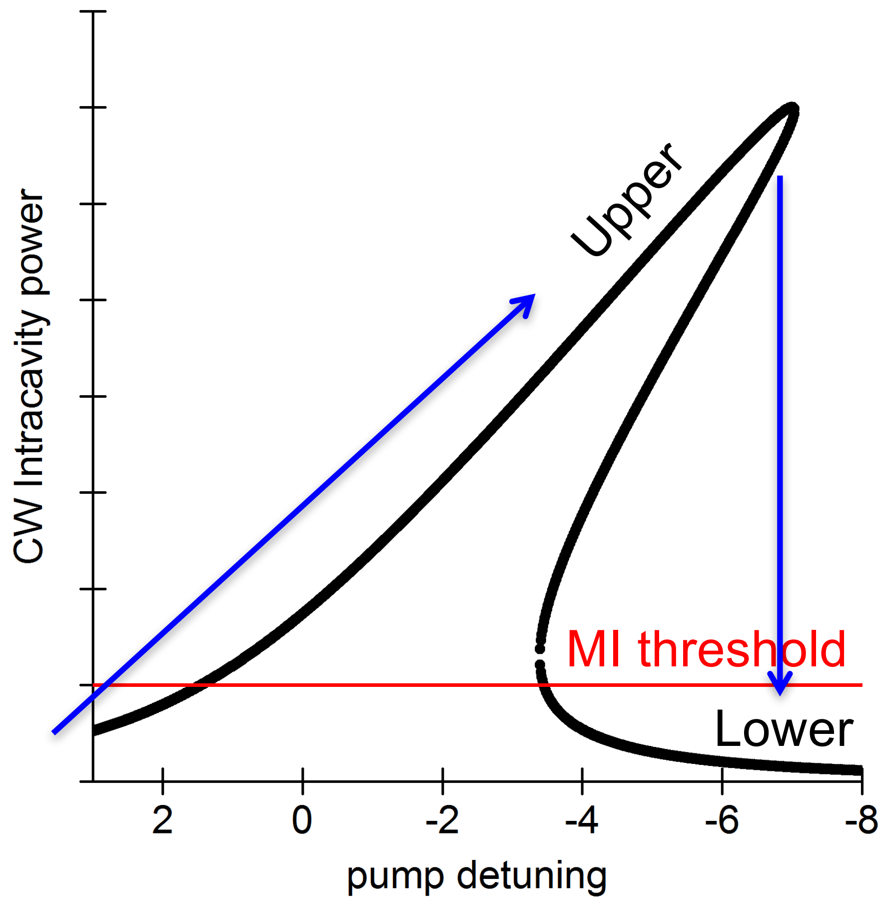
Upper branch:
Modulation instability



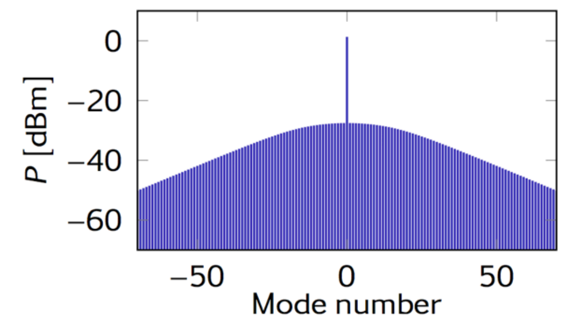


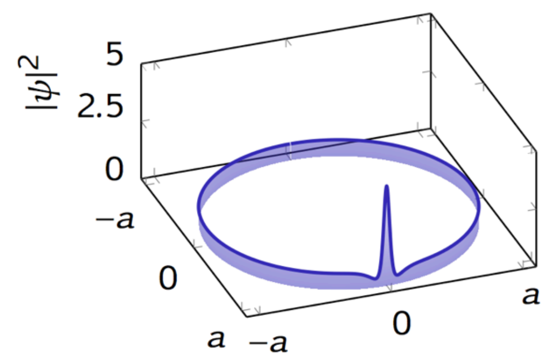


Resonance "tilted" due to Kerr phase shift: n_2I



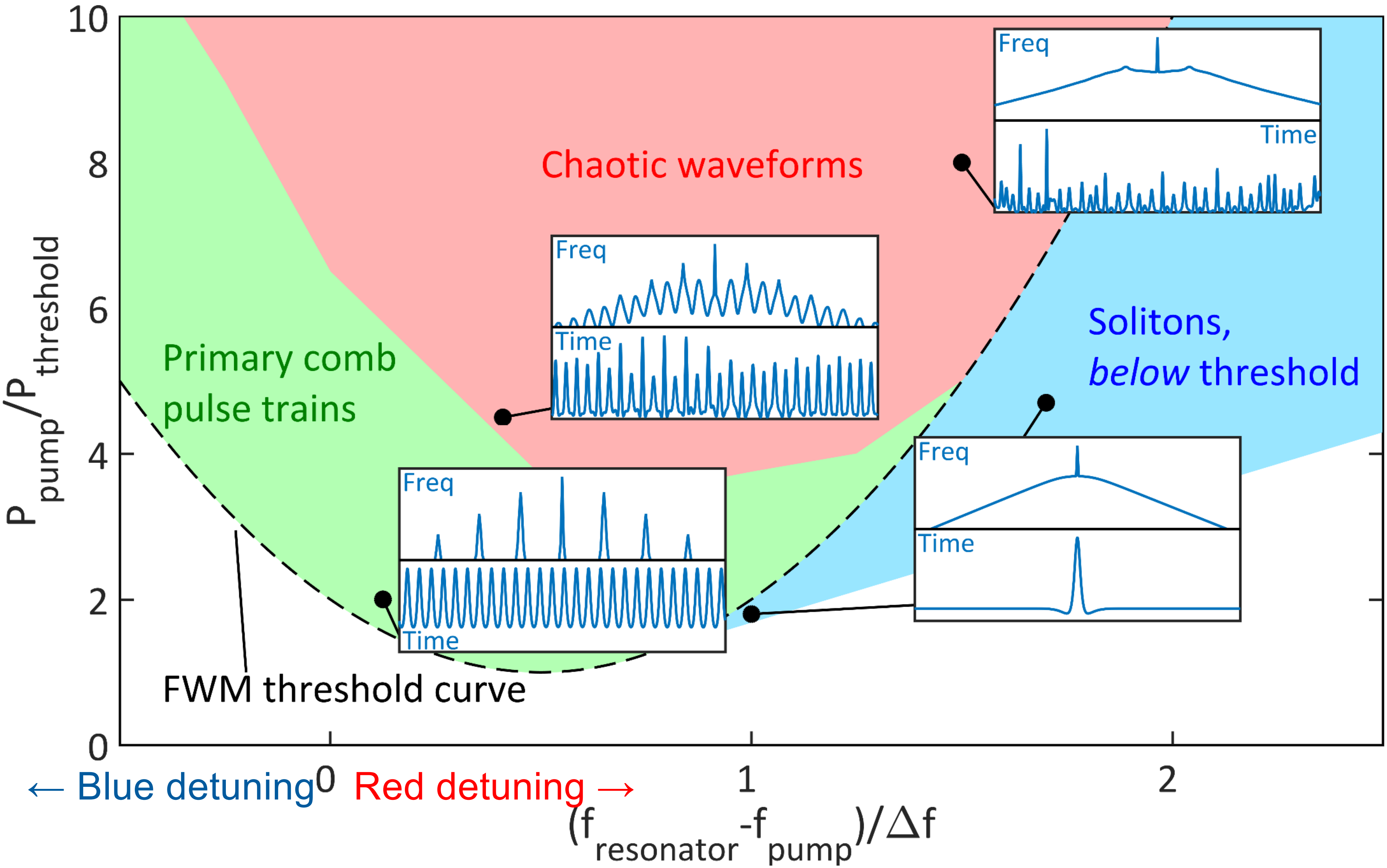
Lower branch:
Cavity soliton





Adapted From: S. Coen and A. Coillet

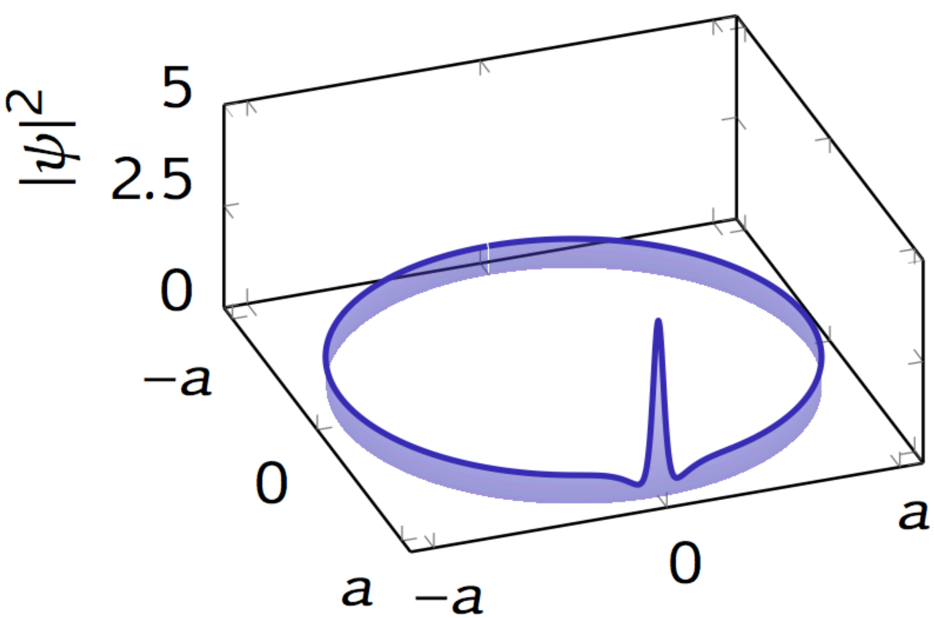
Kerr microcomb 'phase space'

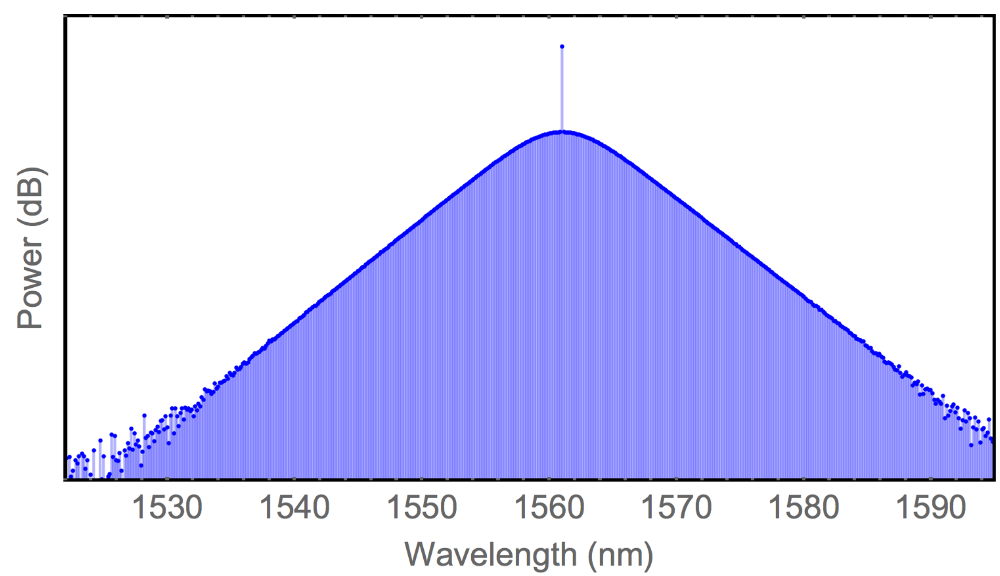


Kerr Solitons

Comb generation governed by **Kerr effect and dispersion**, described by **Lugiato-Lefever equation:**

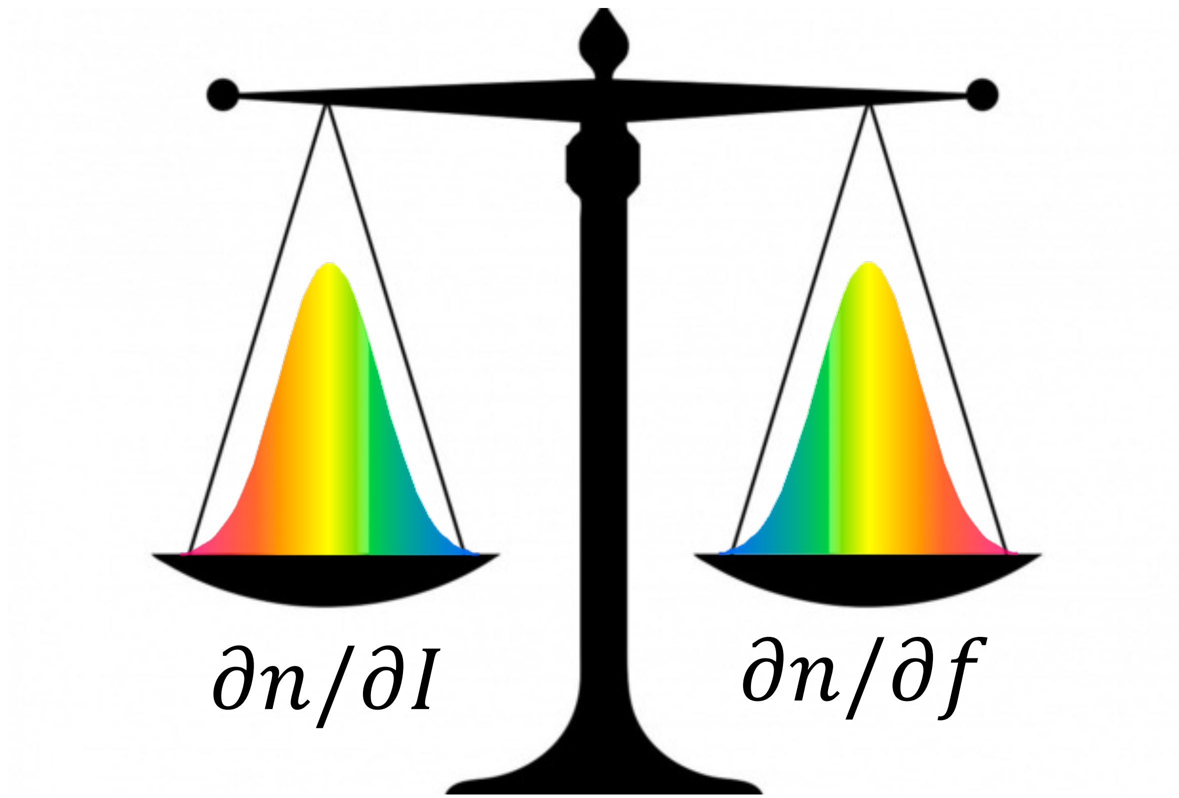
		Loss and detuning		Kerr nonlinearity		Dispersion		Pump
$\frac{\partial \psi}{\partial \tau}$	$=$	$-(1+i\alpha)\psi$	$+$	$i\lvert\psi\rvert^2\psi$	$-$	$i\frac{\beta}{2}\frac{\partial^2 \psi}{\partial \theta^2}$	$+$	F

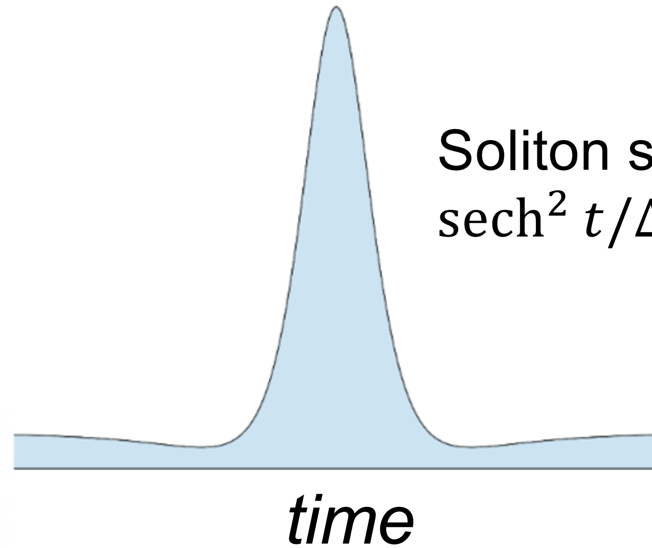




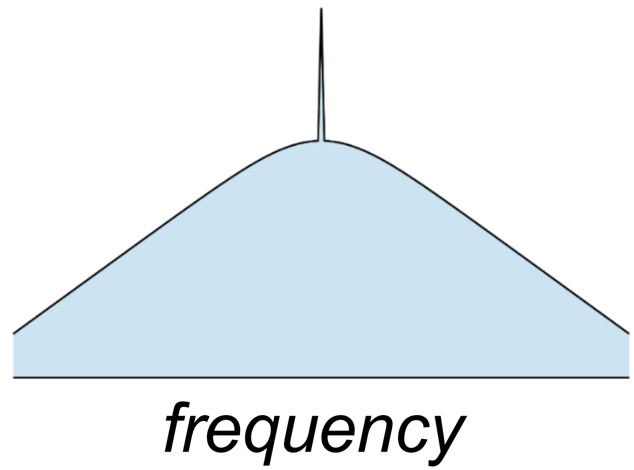
Solitons in microcombs

Soliton: pulse that is able to propagate with fixed width due to balance of nonlinearity and dispersion



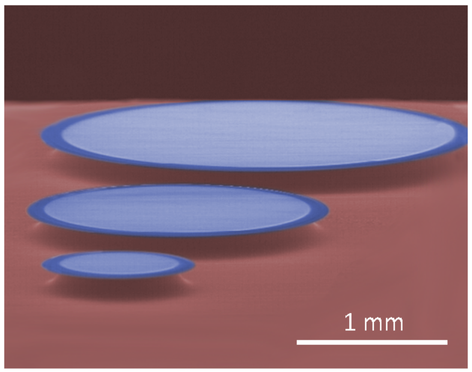


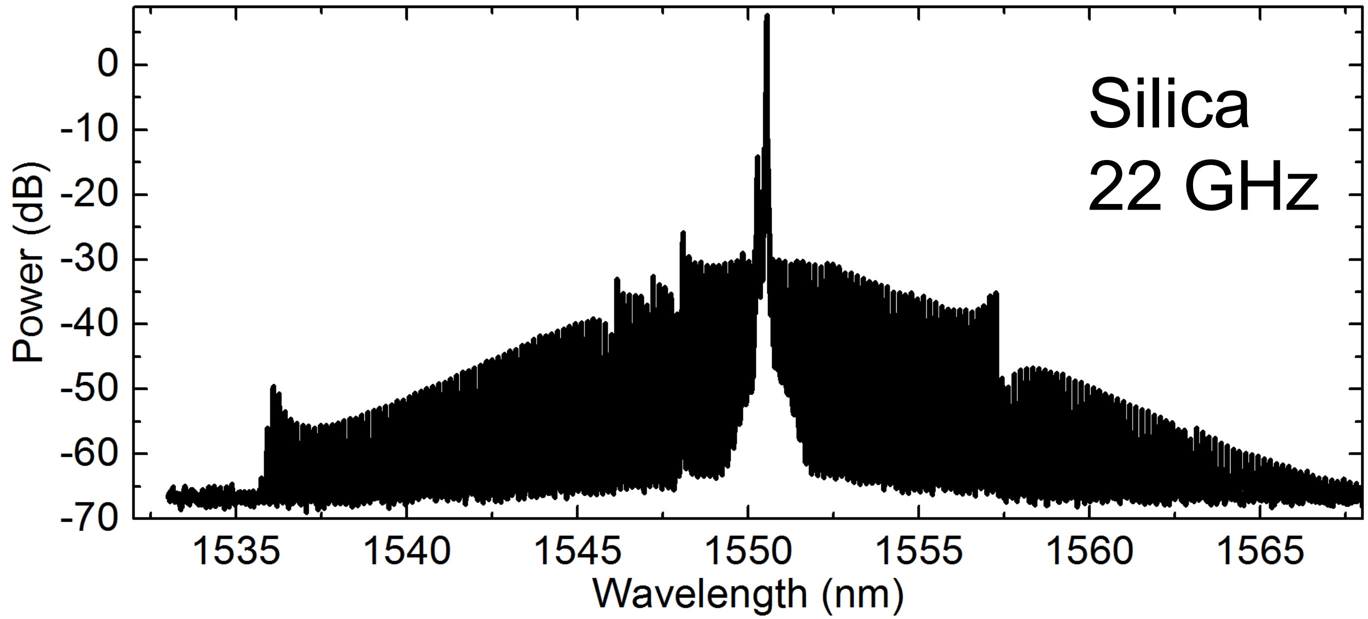
Soliton shape:
$\mathrm{sech}^2\, t/\Delta t$

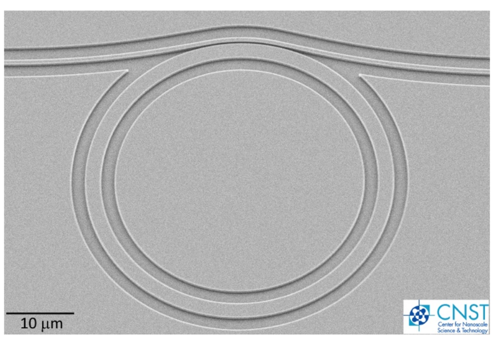


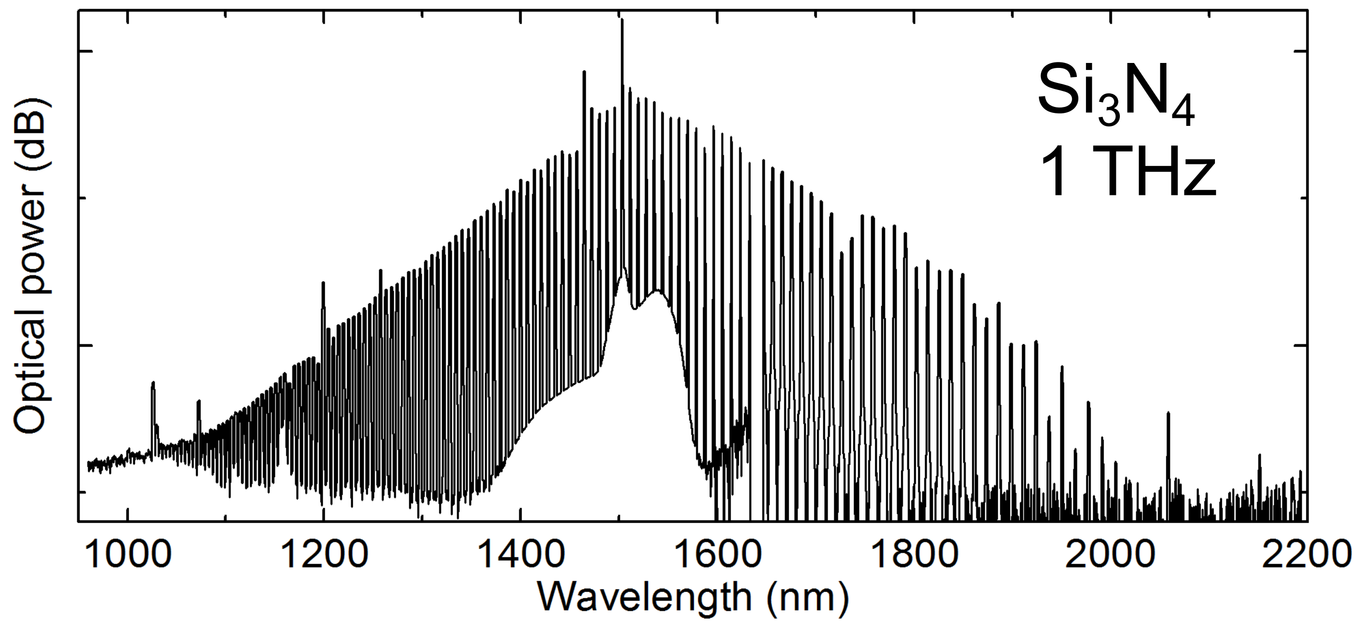
Soliton spectrum:
$\mathrm{sech}^2\, f/\Delta f$

Examples of Solitons







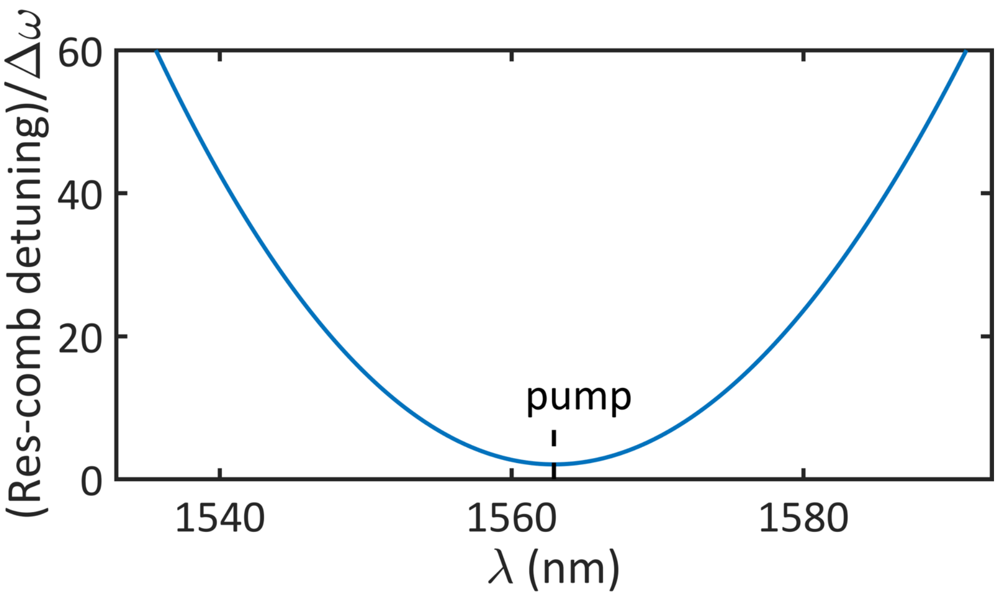


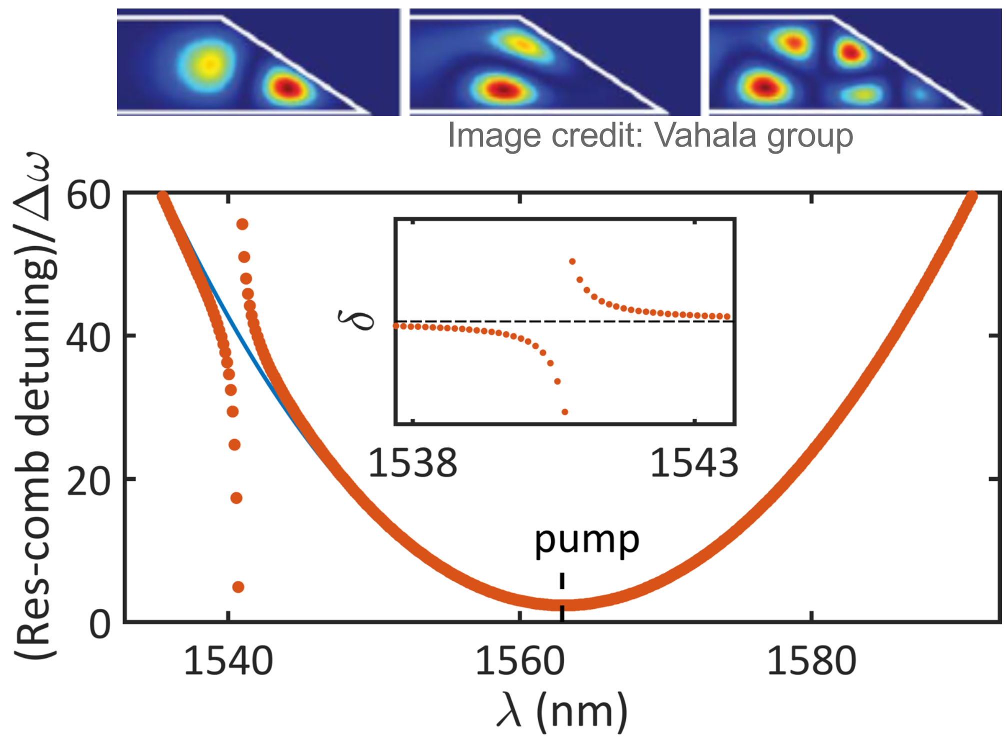
NIST

Comb-resonator detuning & mode crossings

- Resonator has dispersion, but comb has uniform spacing!
- Walk-off between resonator modes and comb modes decreases power in wings

- Perturb resonator mode-structure via coupling with different mode *family* in resonator





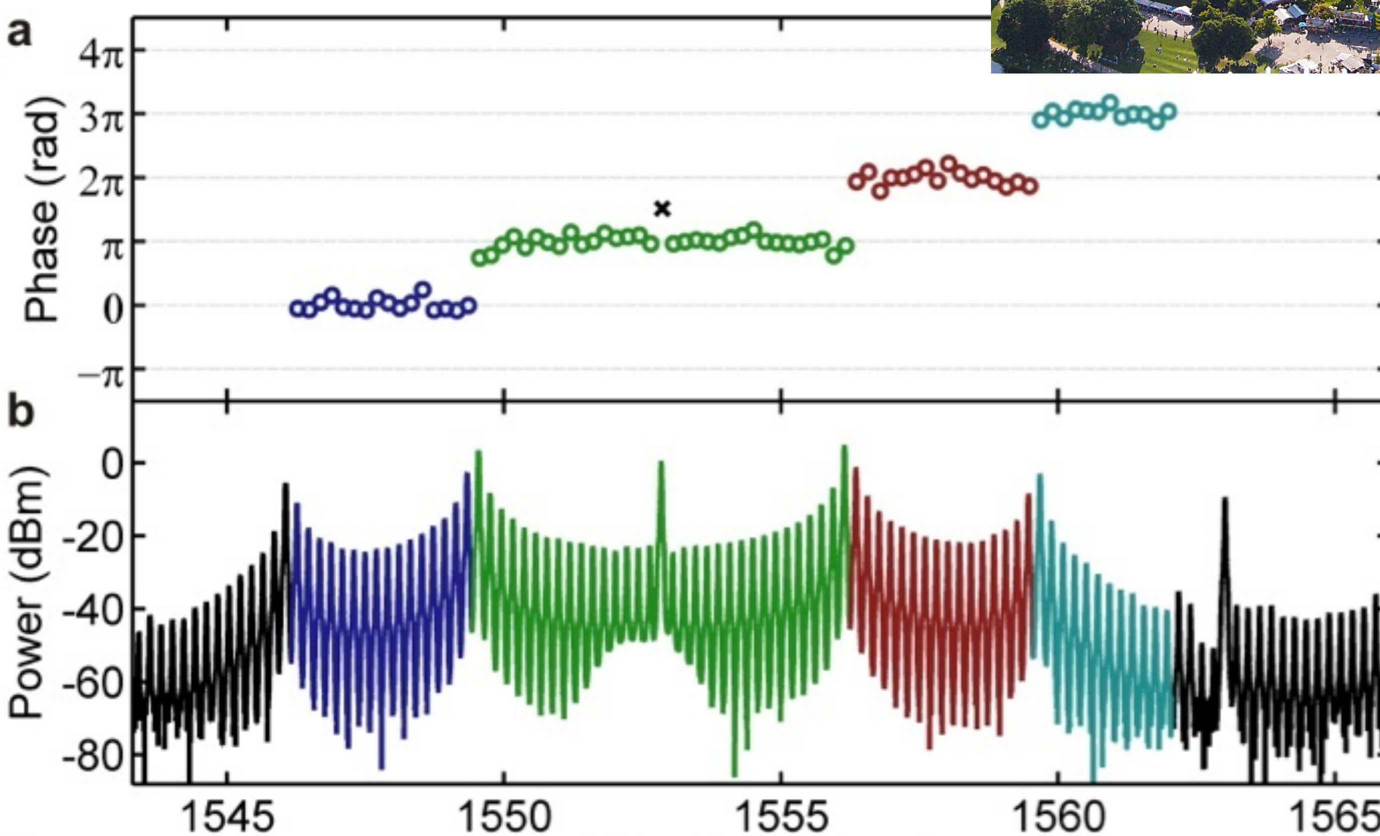
Comb generation locally enhanced/diminished in presence of mode crossing

Phase-Locked Combs

- Sculpted spectral envelope
- π steps in the phase
- Stable, repeatable, stationary waveforms in time

Phase

Power

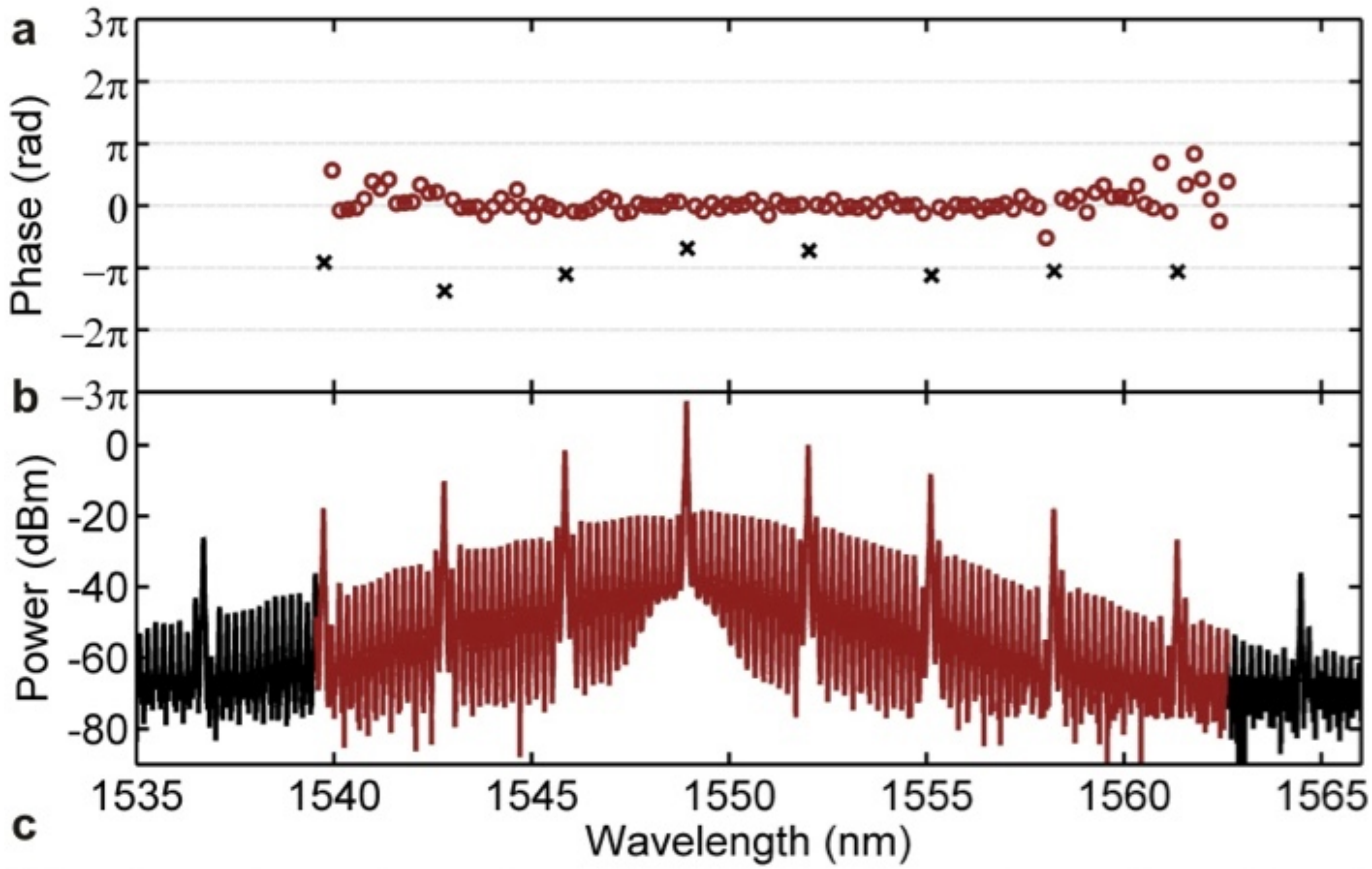


Pascal Del'Haye, Nat. Comm (2015)

Phase-Locked Combs

Phase

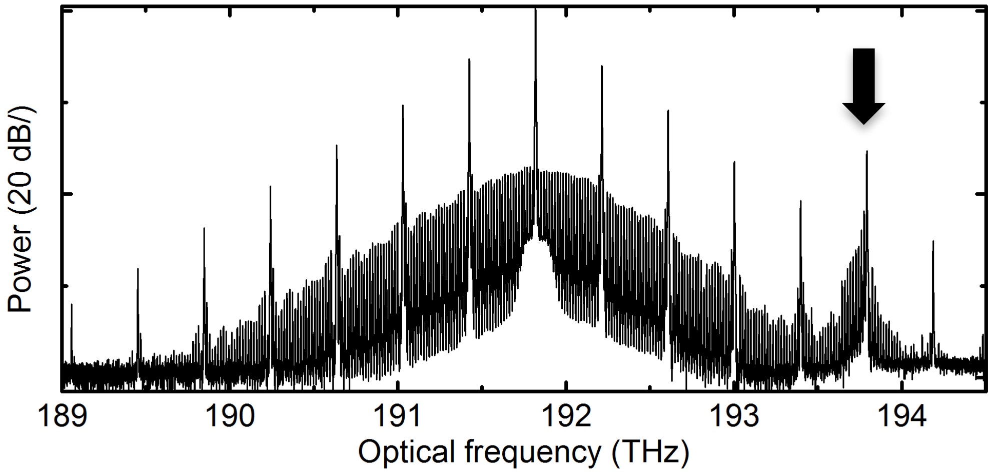
Power



How can we understand these spectra ?

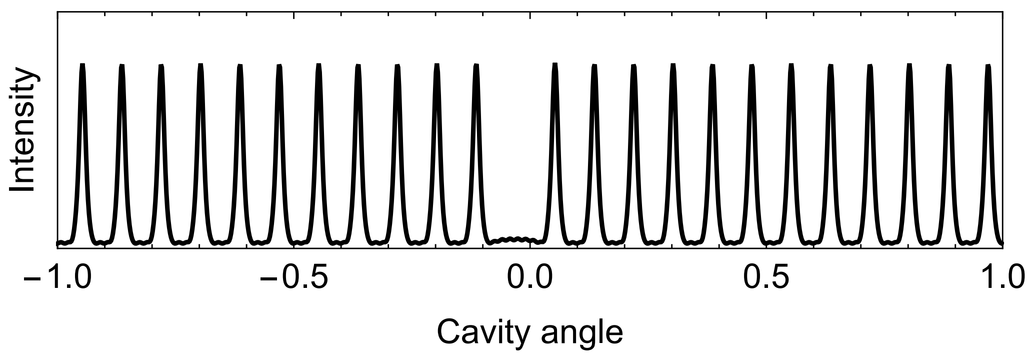
Pascal Del'Haye, Nat. Comm (2015)

Kerr soliton crystals



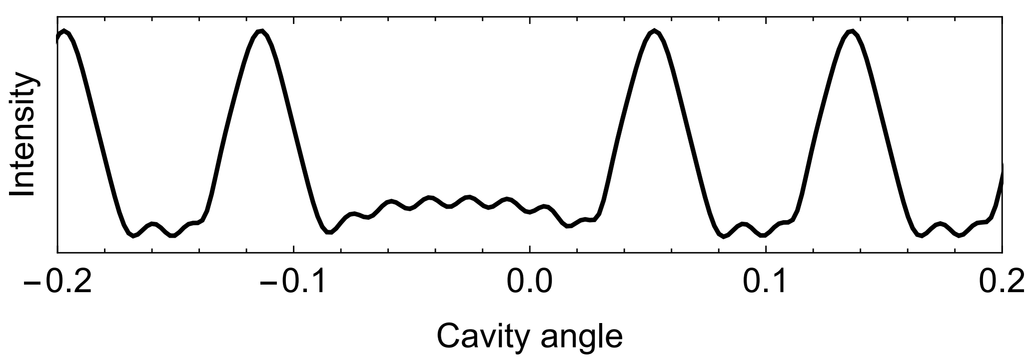
Spectrum:

- Intense comb every 24 modes
- $Sech^2$ profile
- High contrast



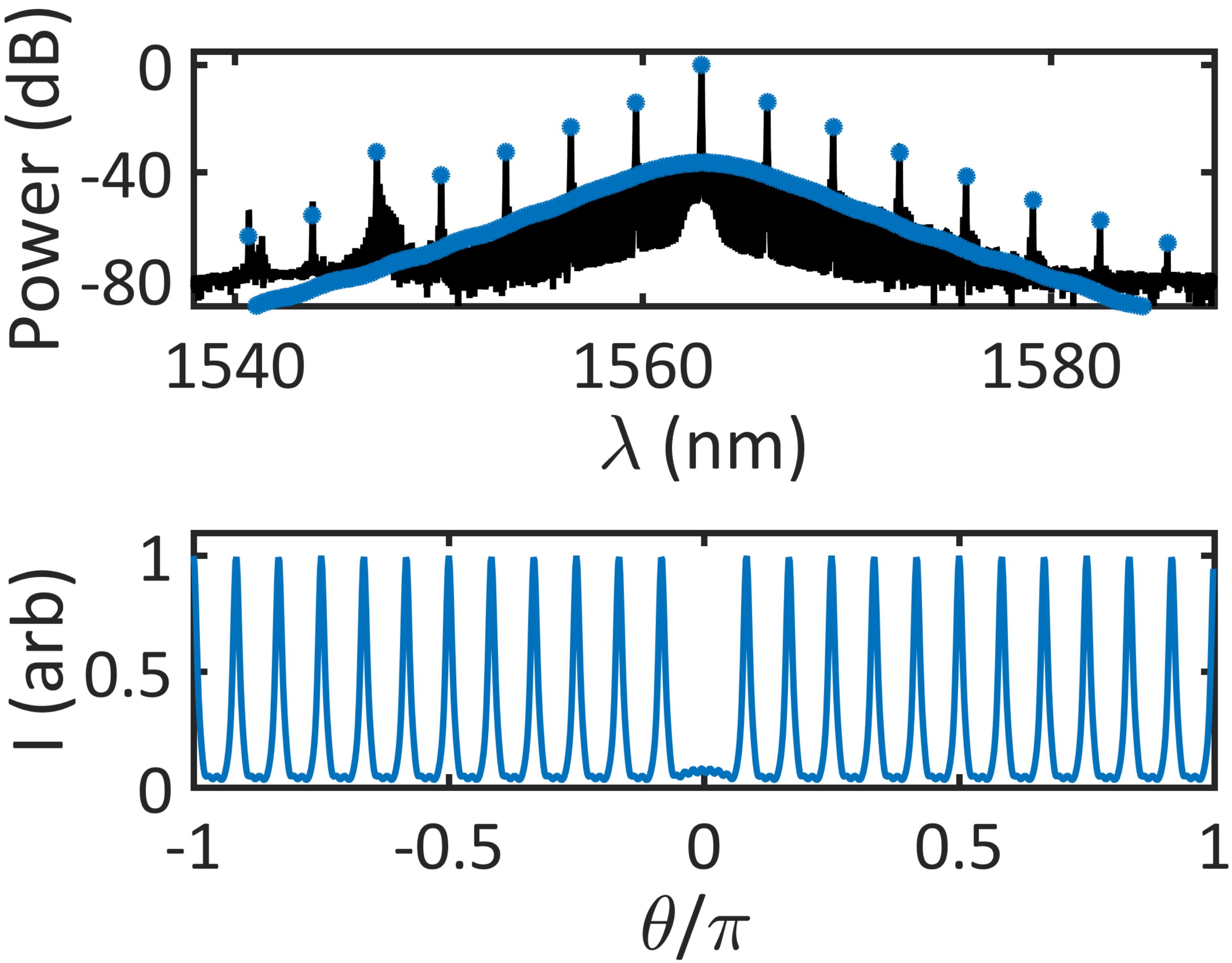
Origins of this spectrum:

- 23 pulses on a *perfect* 24x5 = 120 site lattice
- **Multi-soliton Kerr comb**
- **Not a stable LLE solution!**

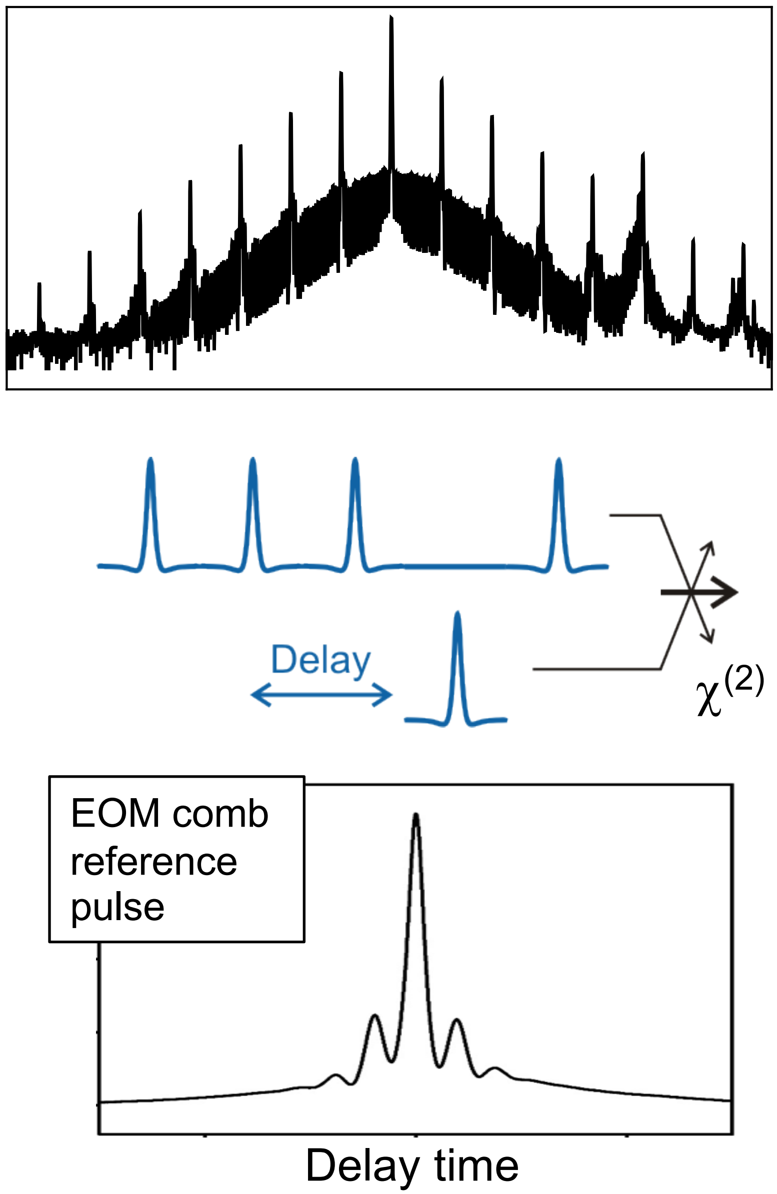


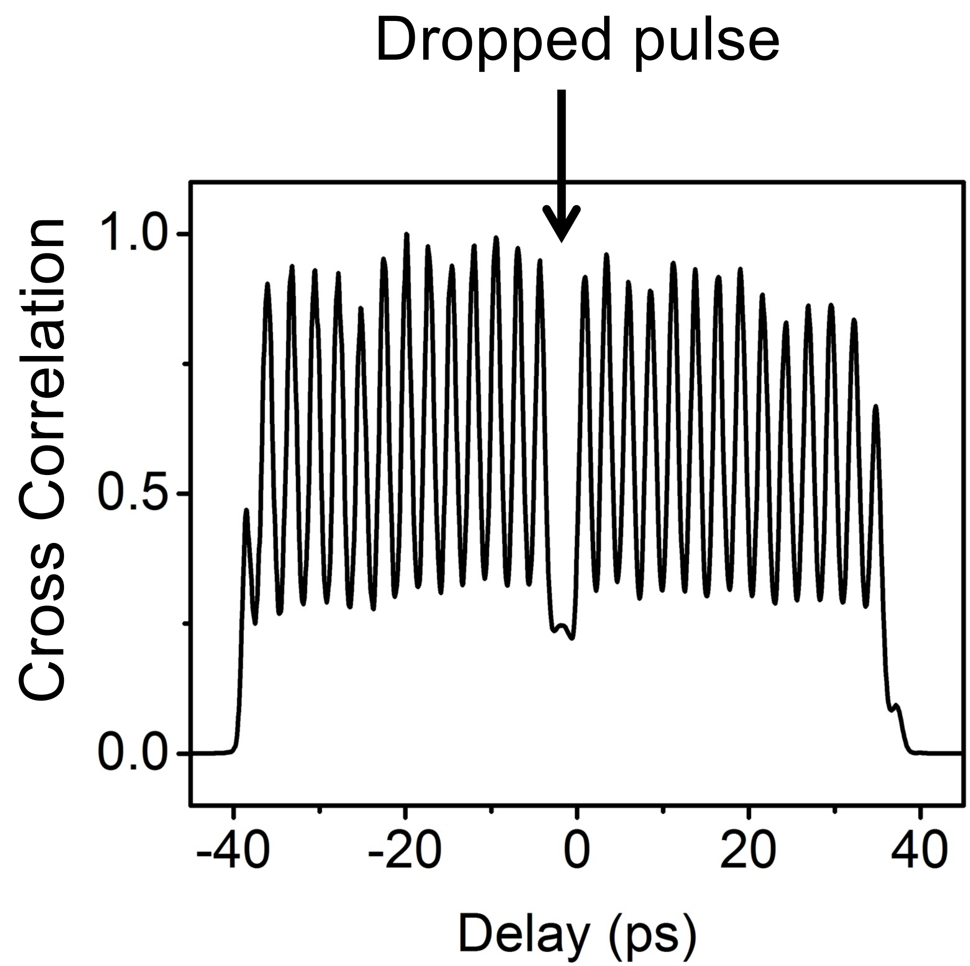
Lattice caused by **mode crossing defects**.

Model/Data agreement

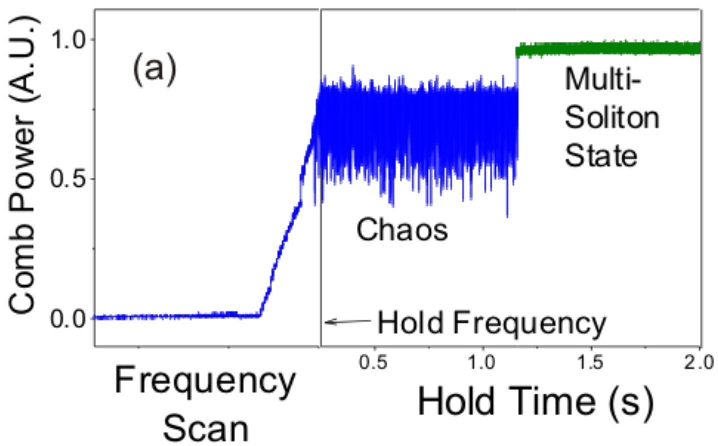


Cross-correlation crystal characterization

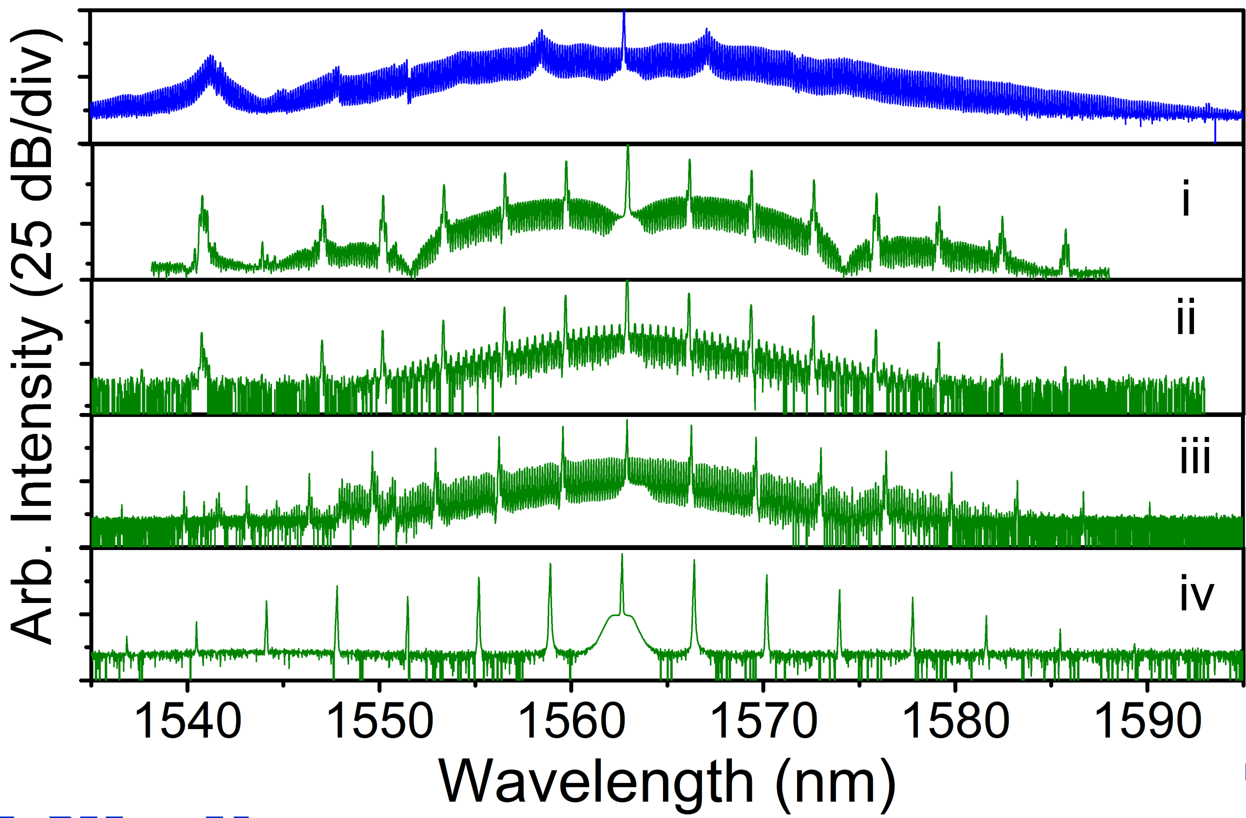


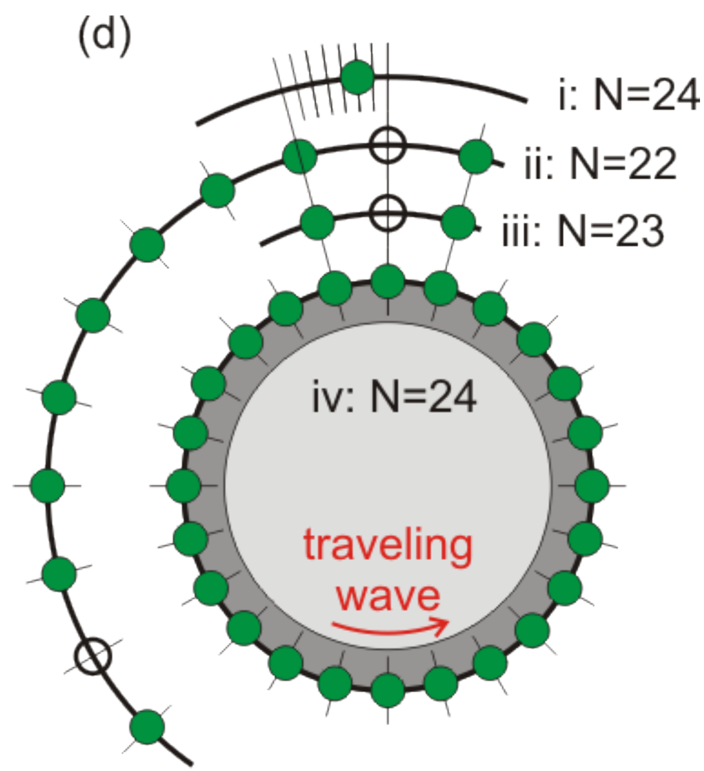


Multi-soliton crystals



- Multi-solitons accessed by slow laser ramp into resonance
- Stable configurations—not always uniformly distributed
- Low-noise, phase-locked spectra

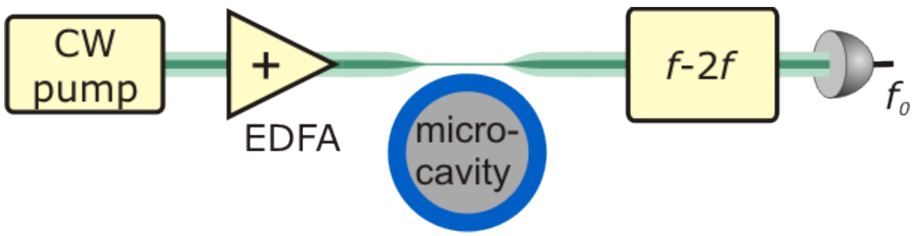




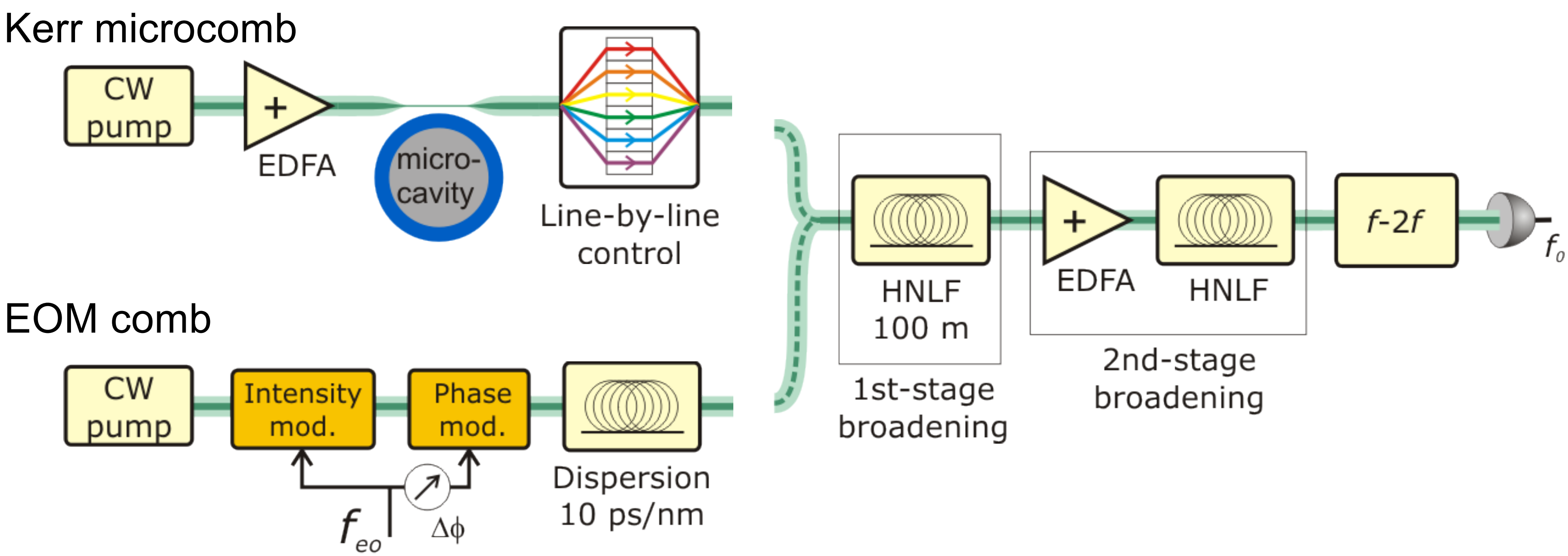
D. Cole, E. Lamb, S. Papp

Self-referencing a microcomb

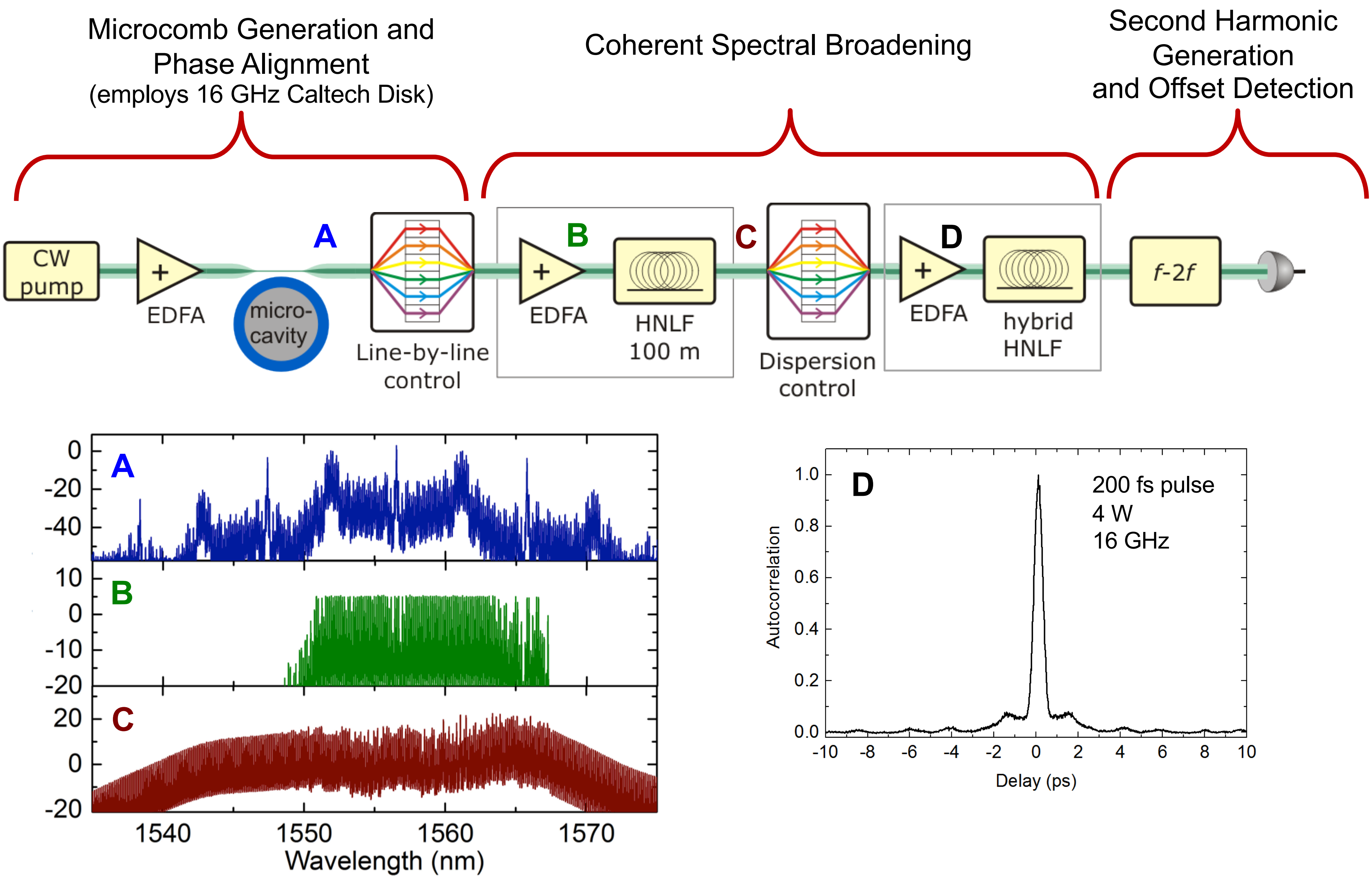
1. Octave spectra on-chip



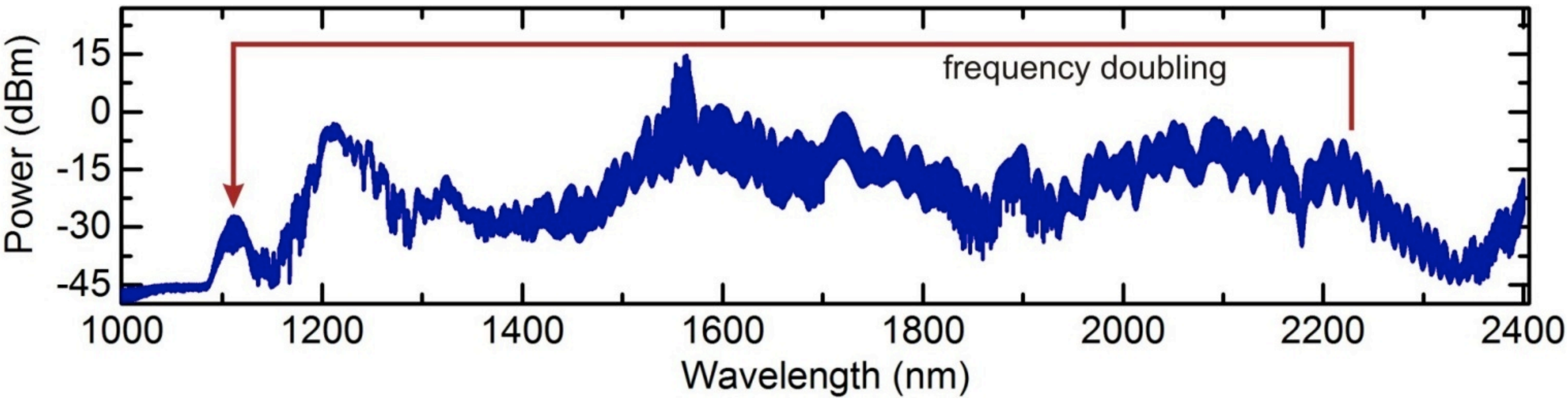
2. Spectral broadening outside resonator – ultrafast pulse broadening

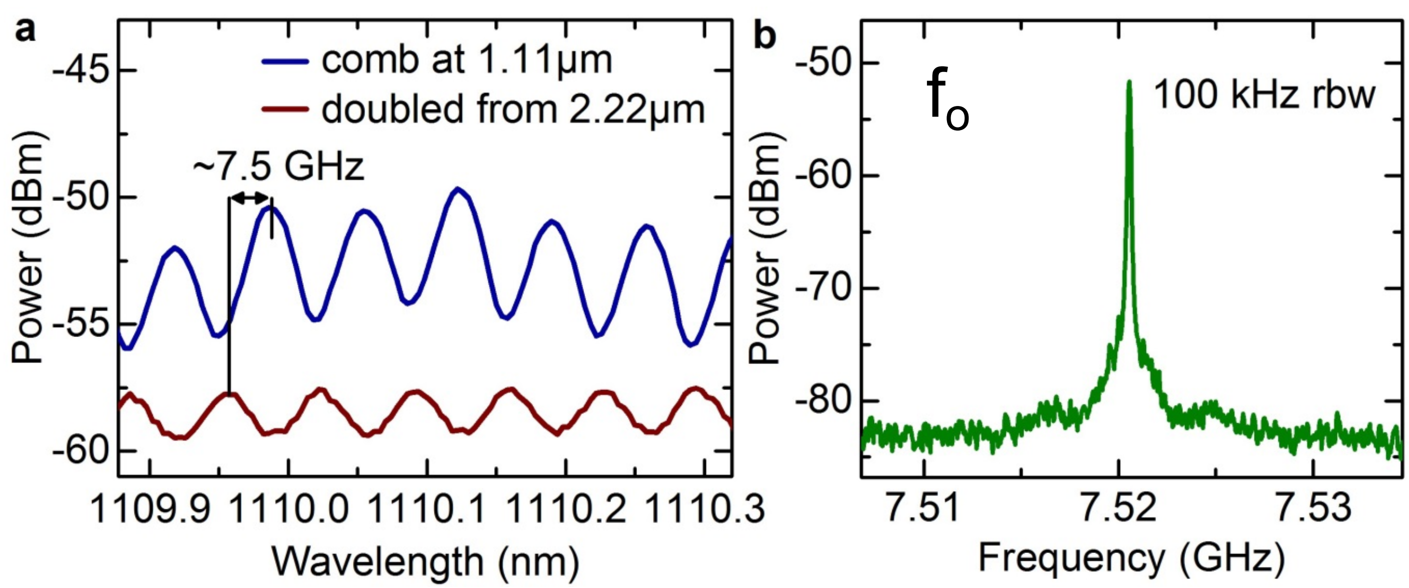


Self-Referencing a Microcomb



Self-Referencing a Microcomb

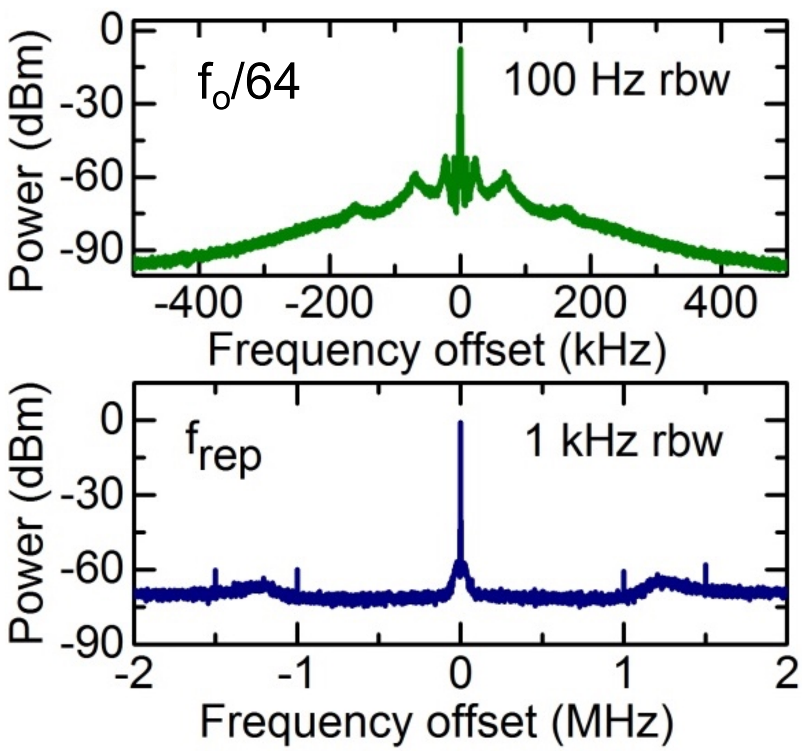




Pascal Del'Haye, Nature Photon (2016)

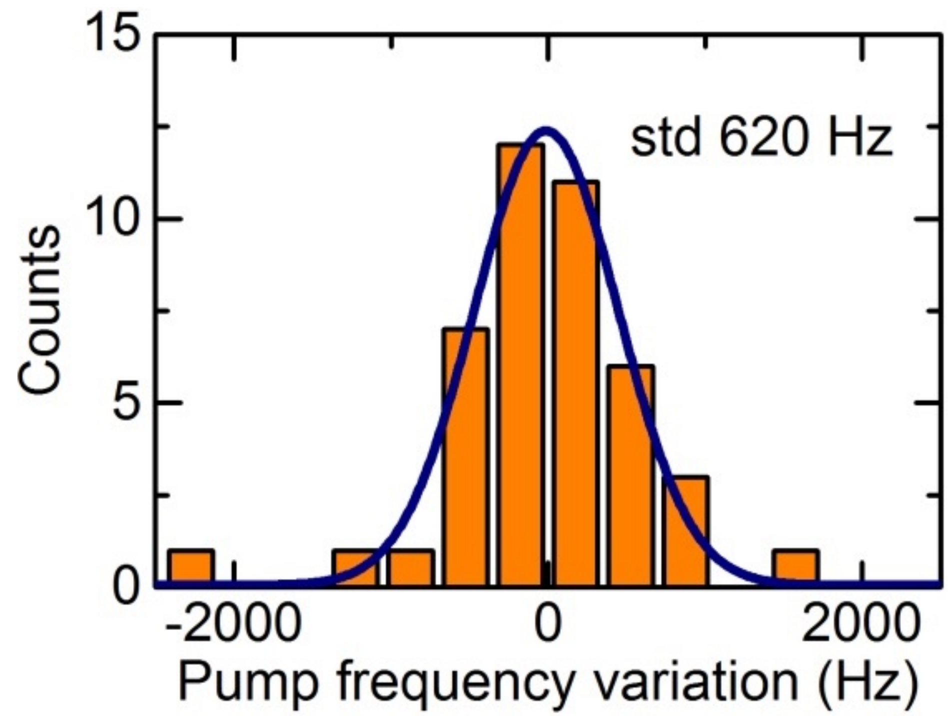
A frequency stabilized microcomb!

Phase-locked:
f_o (pump power)
f_{rep} (pump tuning)



Measure pump frequency:

$$\nu_{pump} = Nf_{rep} + f_o$$

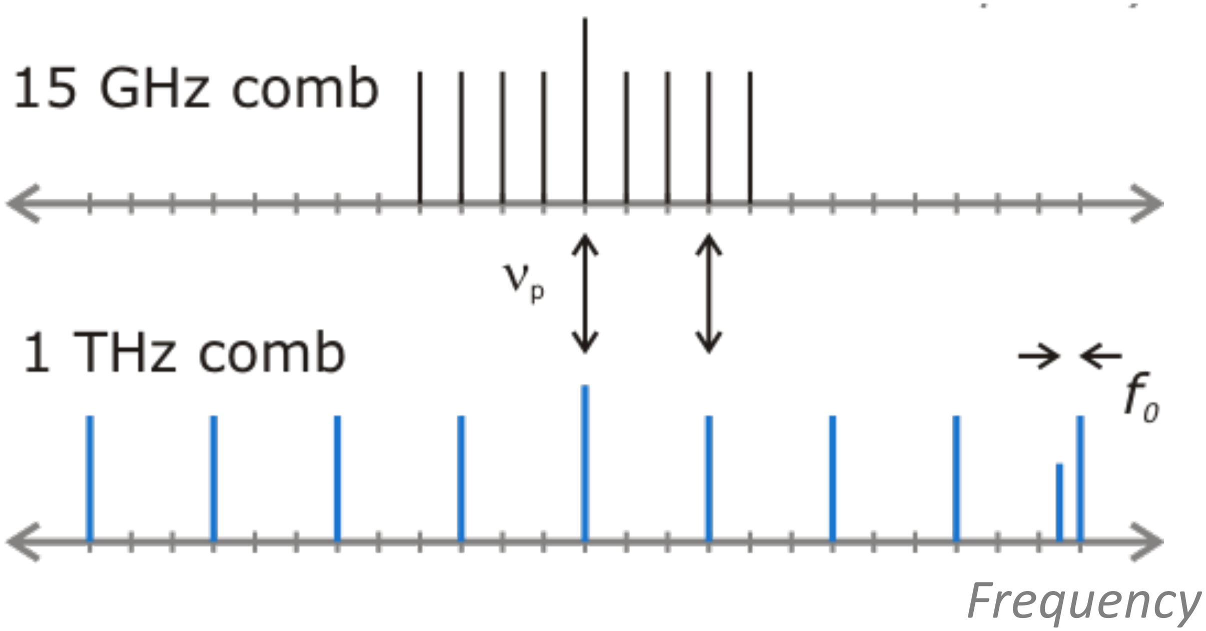


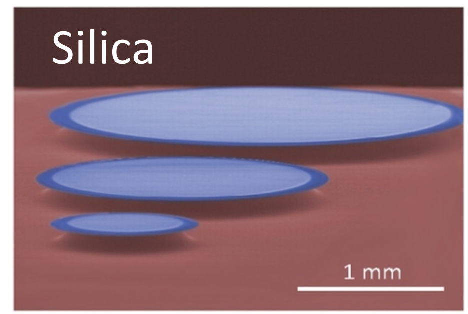
Fluctuations at level of H-maser

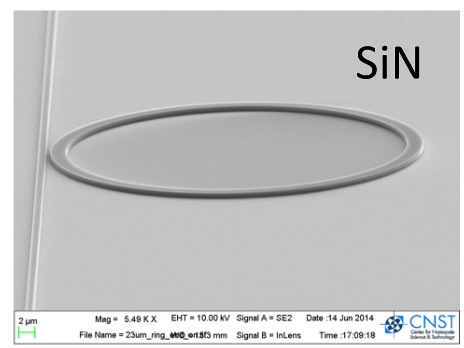
Pascal Del'Haye, Nature Photon (2016)

Self-referencing on a chip?

Goal: An octave-span, self-referenced microcomb on a chip
Challenges: Integration, power, frequency control & basic nonlinear optics
Approach: Dual reduction gear 200 THz → 1 THz → 15 GHz
Leverage: Photonic integration (pump laser, PPLN, photodiodes)



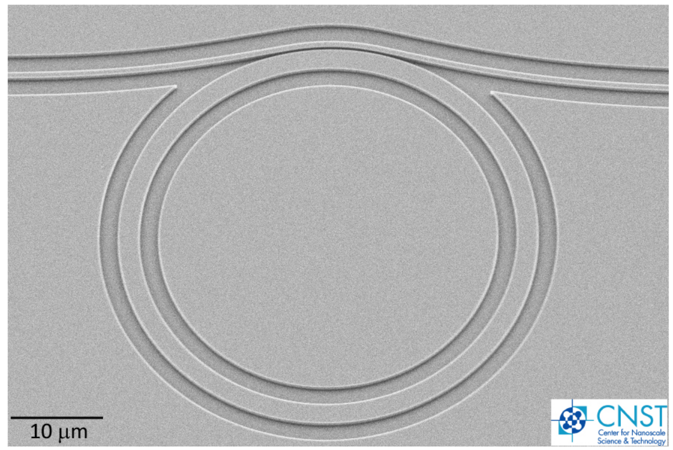




NIST

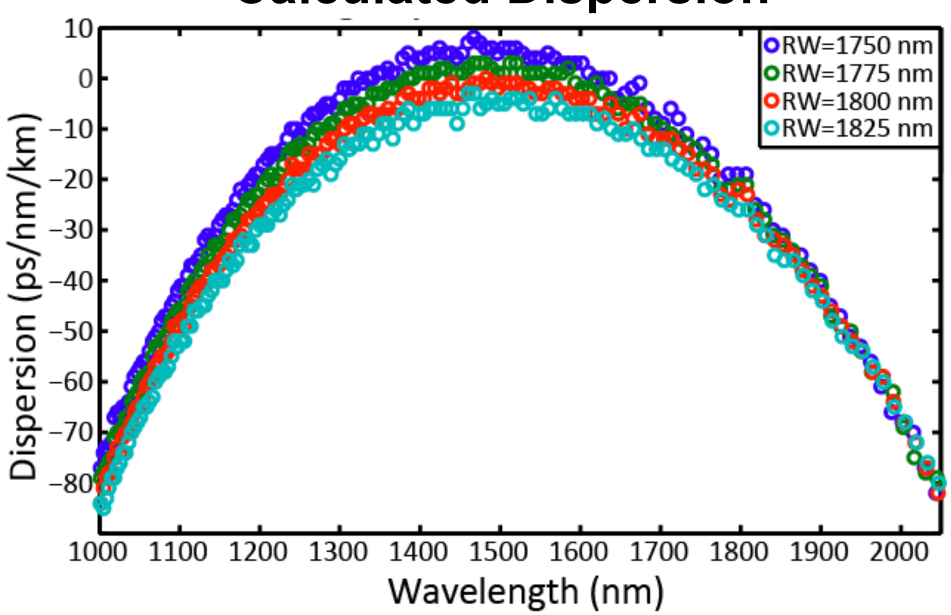
THz microcomb chip

1 THz SiN resonator

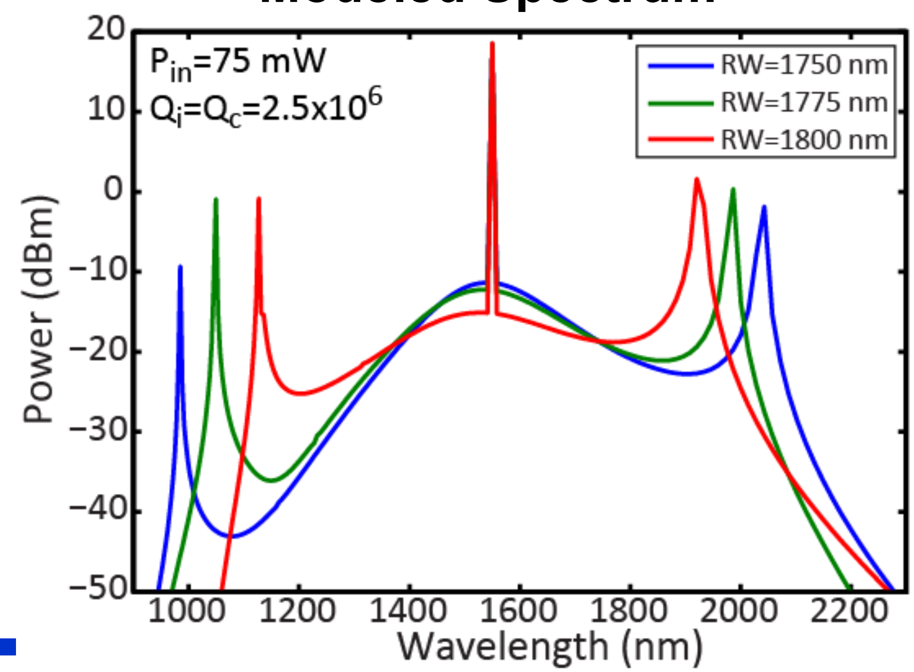


Kartik Srinivasan
Qing Li
Daron Westly

Calculated Dispersion



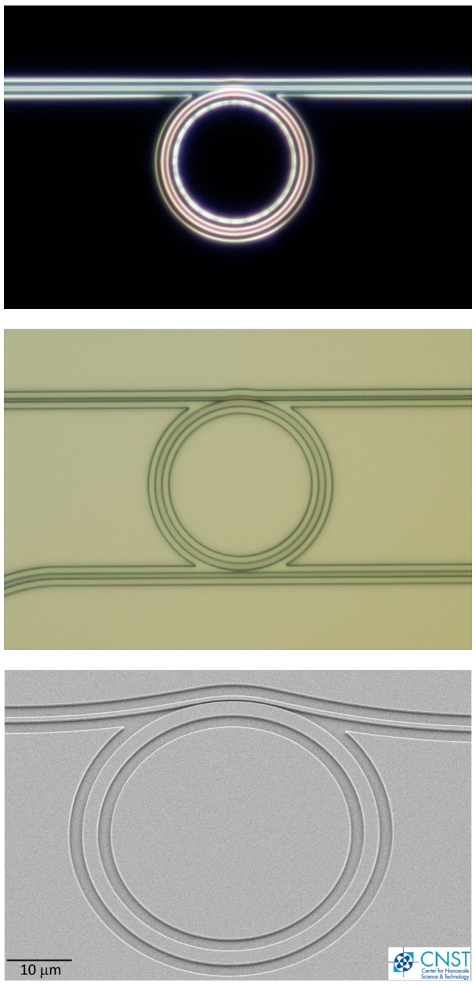
Modeled Spectrum

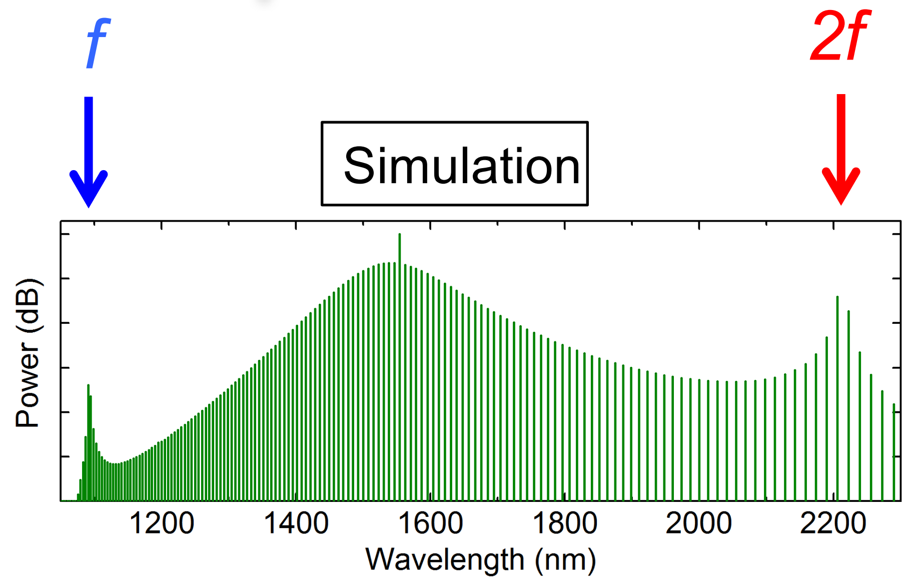


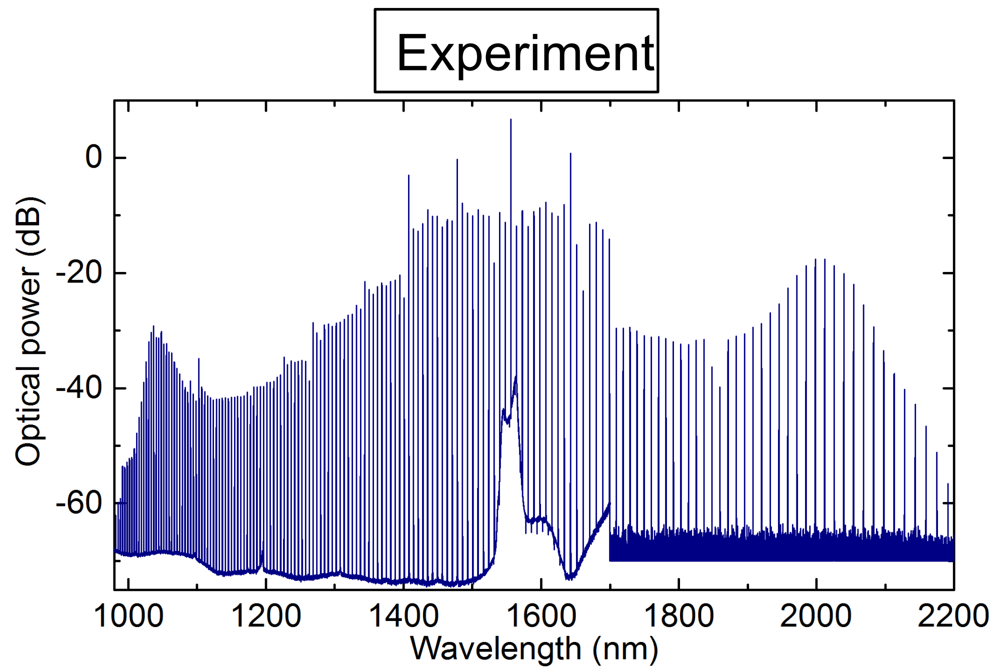
NIST

Octave Span & Dual Dispersive Waves

Goal: Octave bandwidth on chip





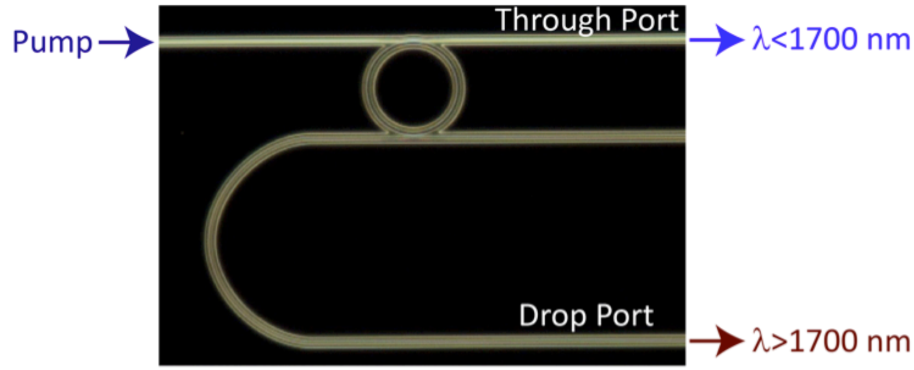


Q. Li OSA FiO postdeadline 2015

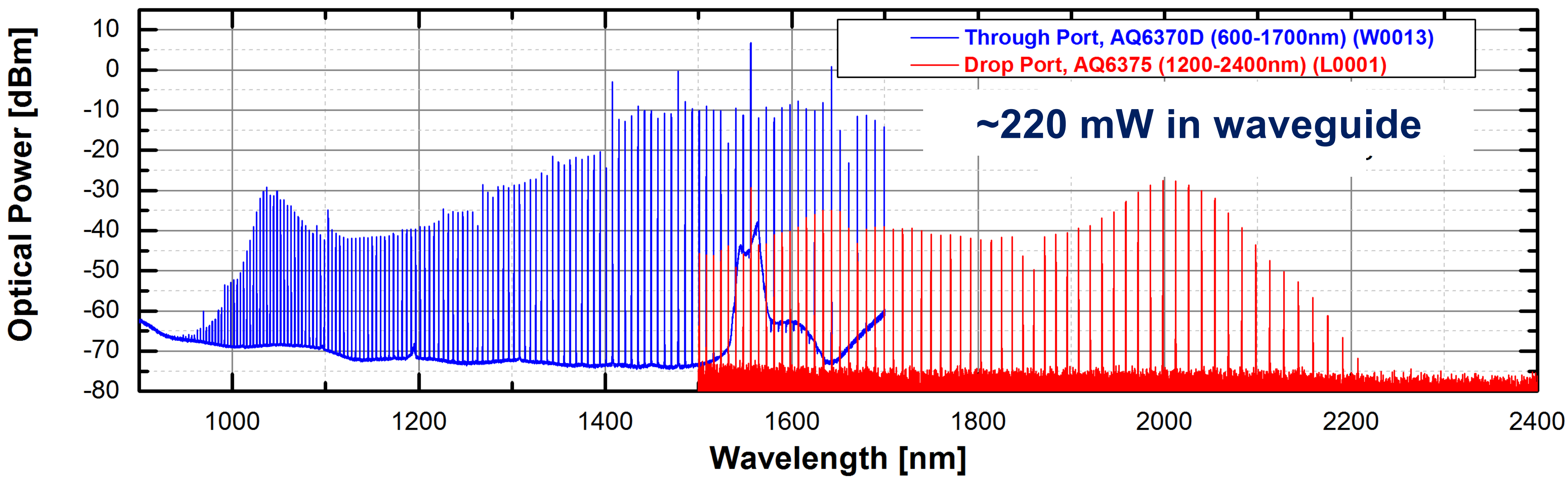
NIST

Octave Span & Dual Dispersive Waves

- dual dispersive waves via dispersion engineering
- “through” and “drop” ports provide optimal out-coupling of 1000 and 2000 nm

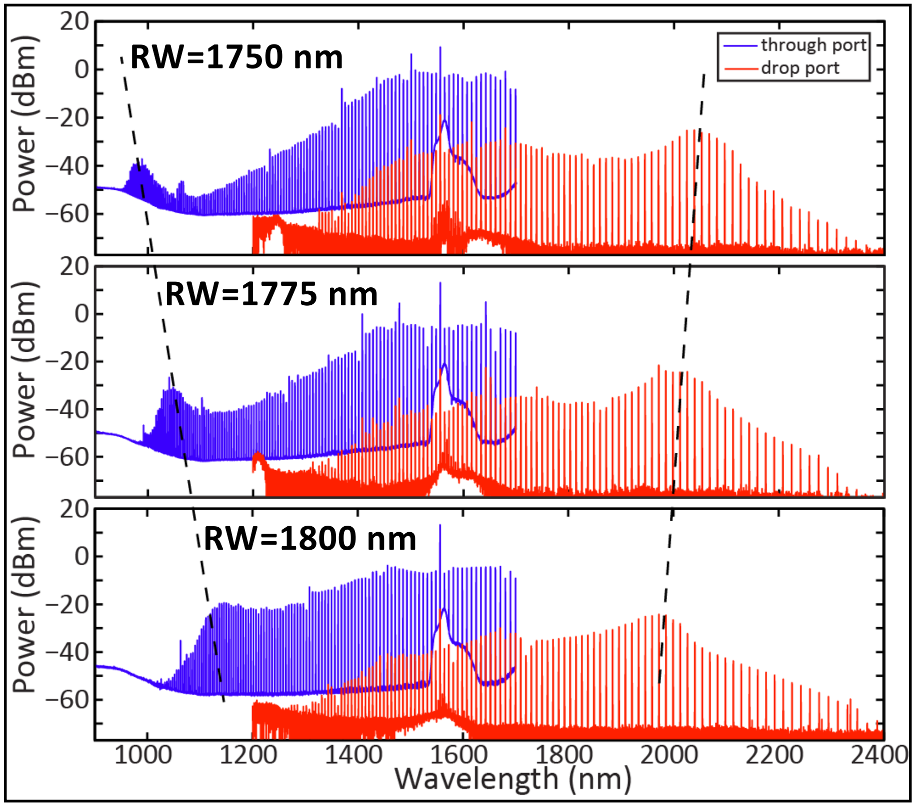


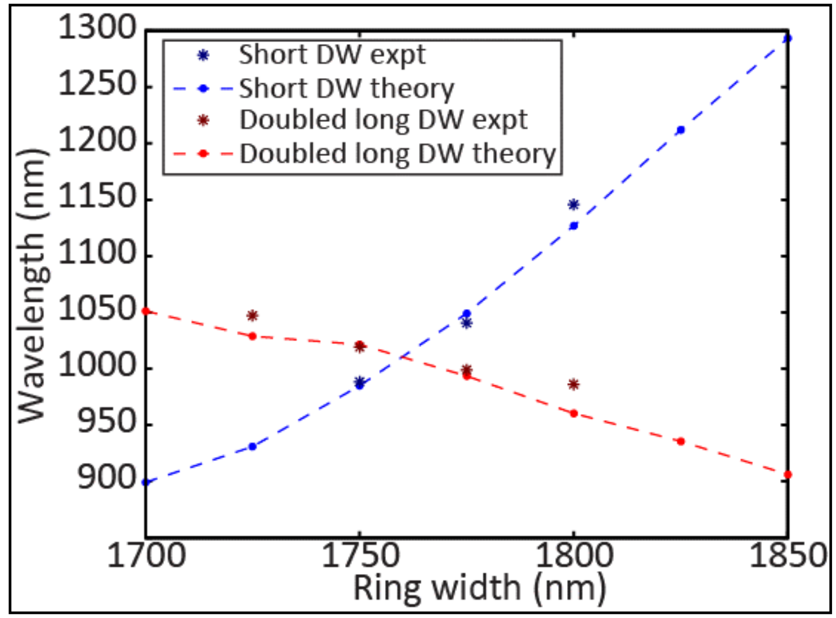
Travis Briles



Spectra enable self-referencing!

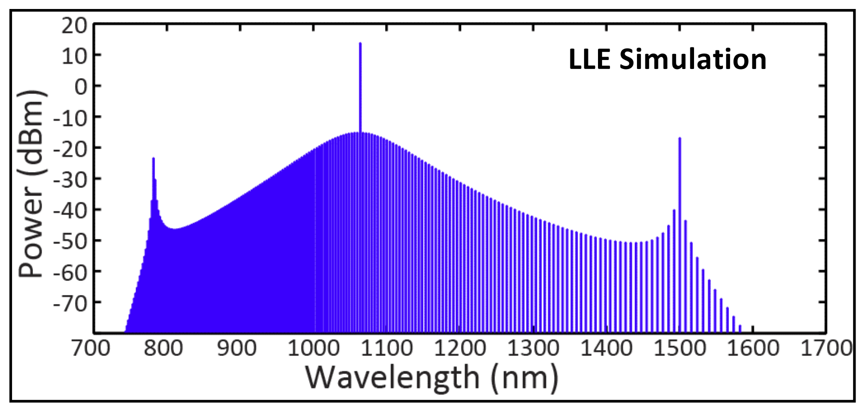
Control of dispersive wave positions





Fine control of dispersion (e.g. via ring width) for harmonic (*f*-2*f*) dispersive waves

Adjust dispersion (coarse change to resonator cross-section) and pump wavelength to shift comb to other desirable spectral windows



NIST

Q. Li et al, *Frontiers in Optics,* post-deadline, FW6C.5 (2015)

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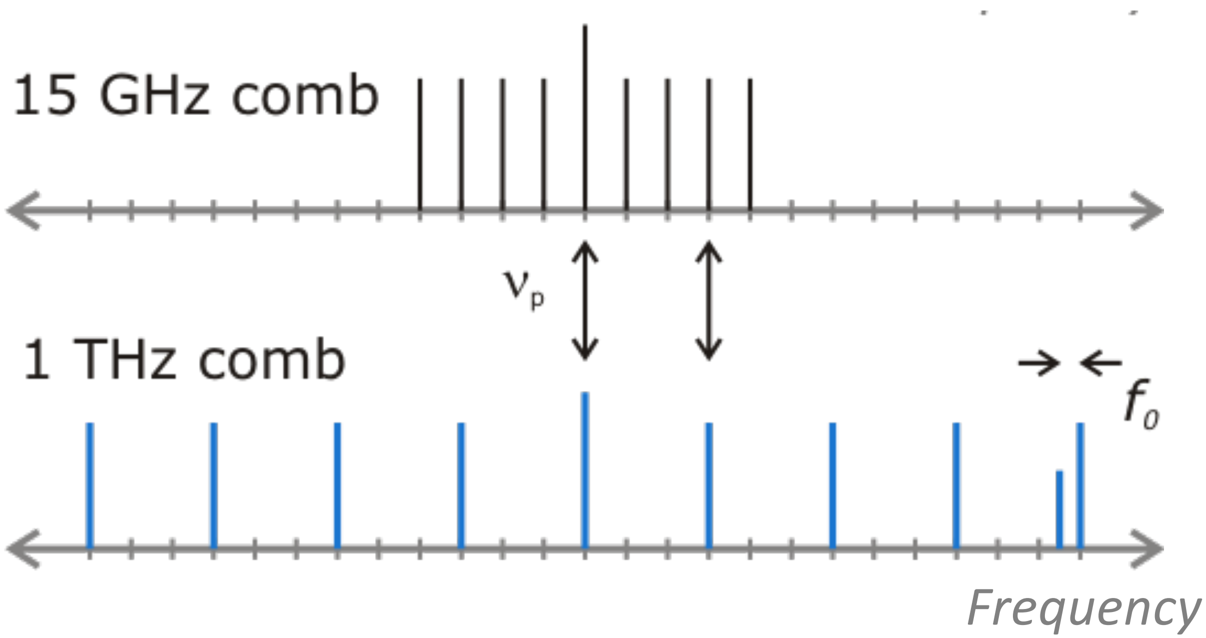
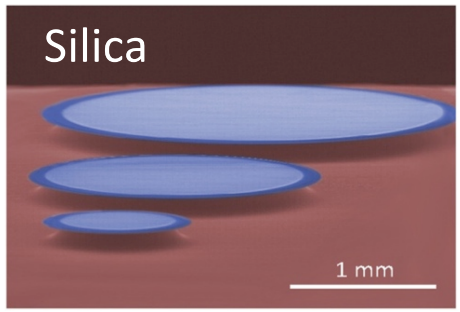
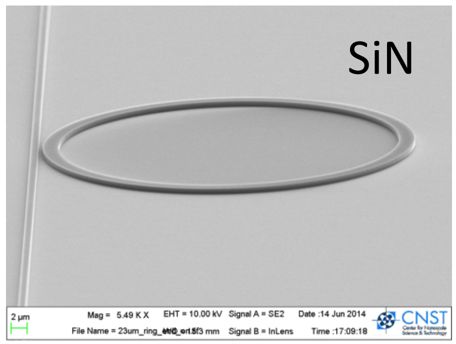
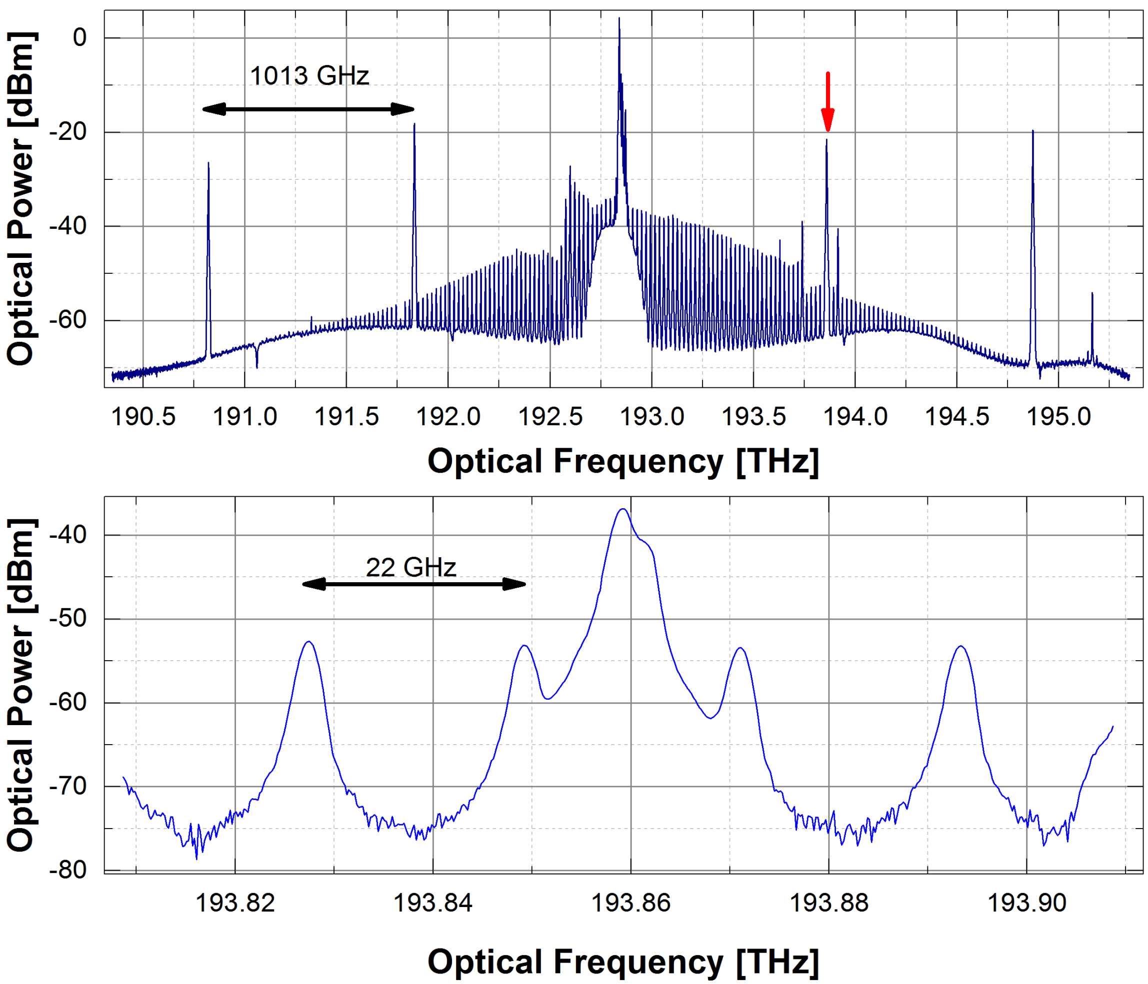
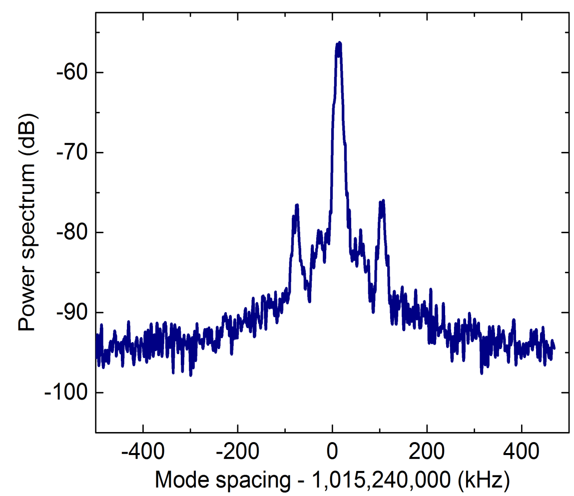






Counting the THz Rep. Rate

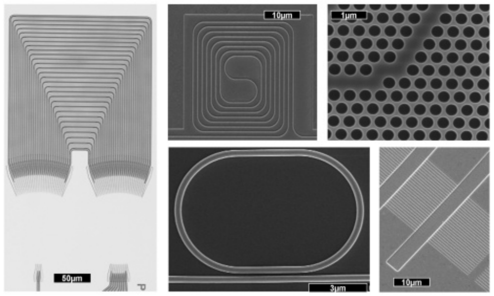


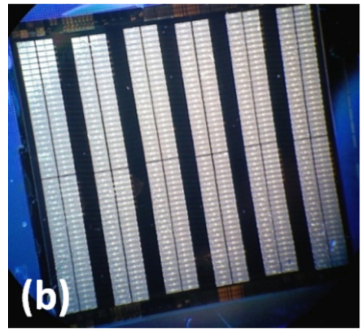


Brilles, Drake, Stone (NIST)

Heterogeneous Integration on Silicon

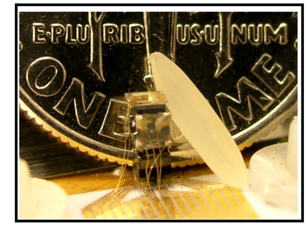
Waveguids, Filters, Splitters

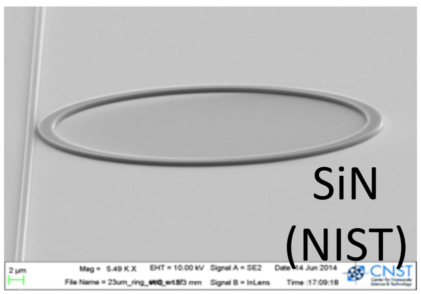


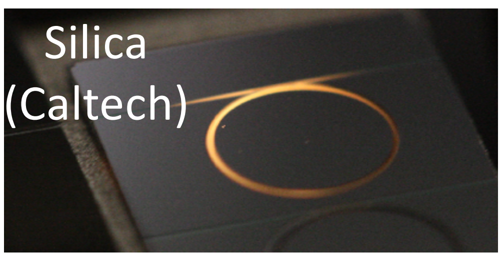


1550 nm lasers and SOAs (UCSB, Aurrion)

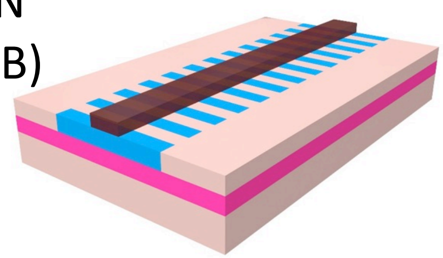
Atoms? (Kitching, et al, NIST)

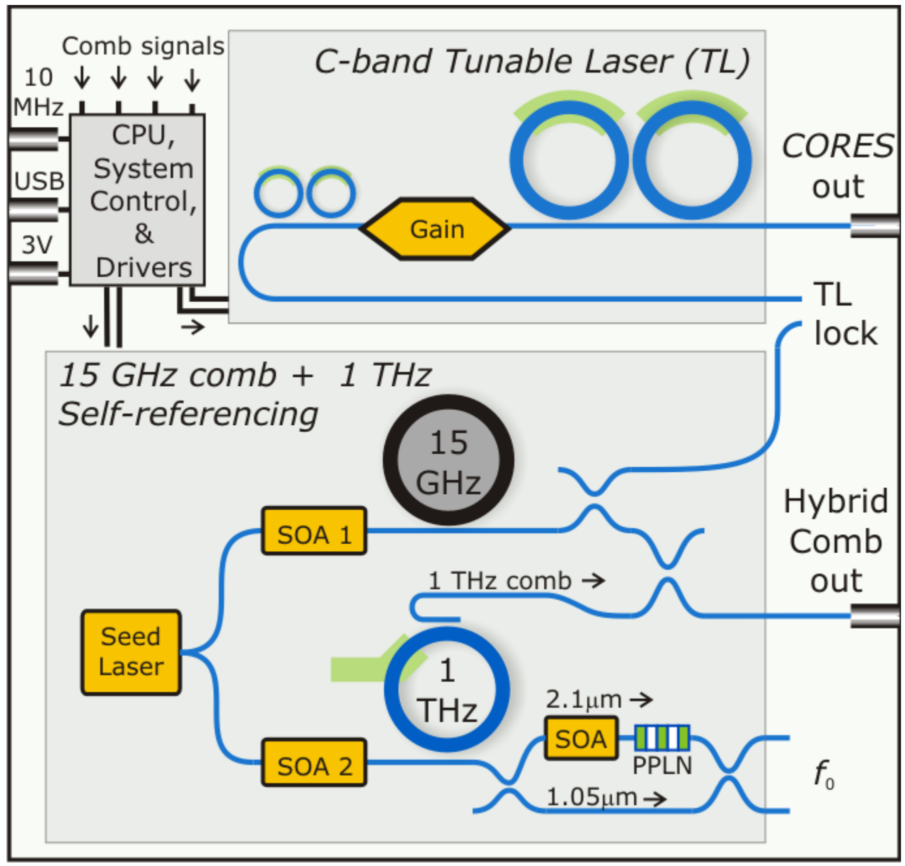






PPLN (UCSB)





Heck et al. JSTQE 2013, Bowers, IEEE FCS (2016)

Getting the Technology out of the Lab…

Atomic “wristwatch”
http://www.LeapSecond.com/

Thank you!

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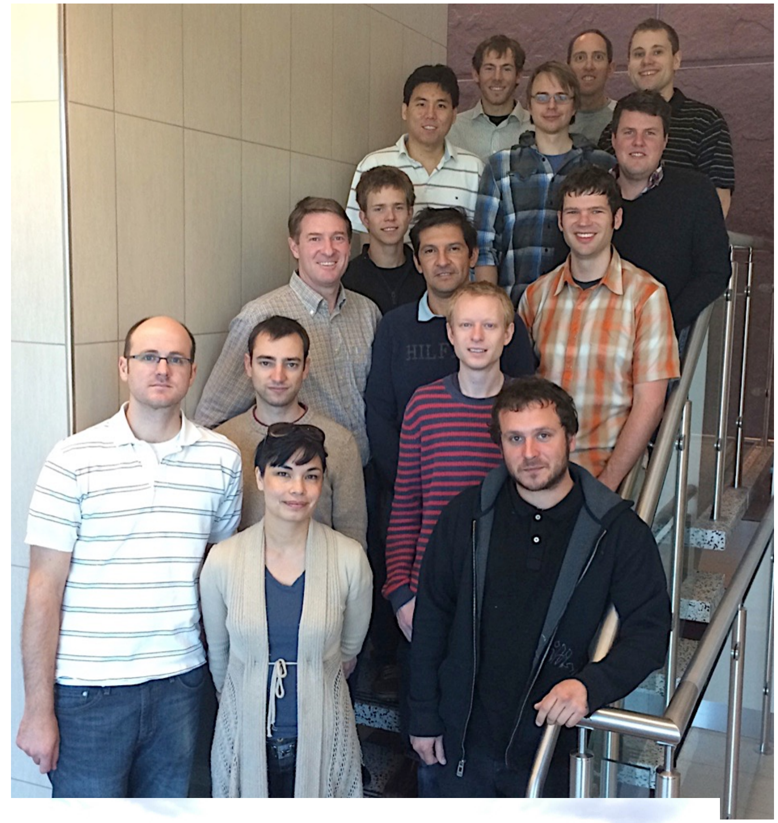
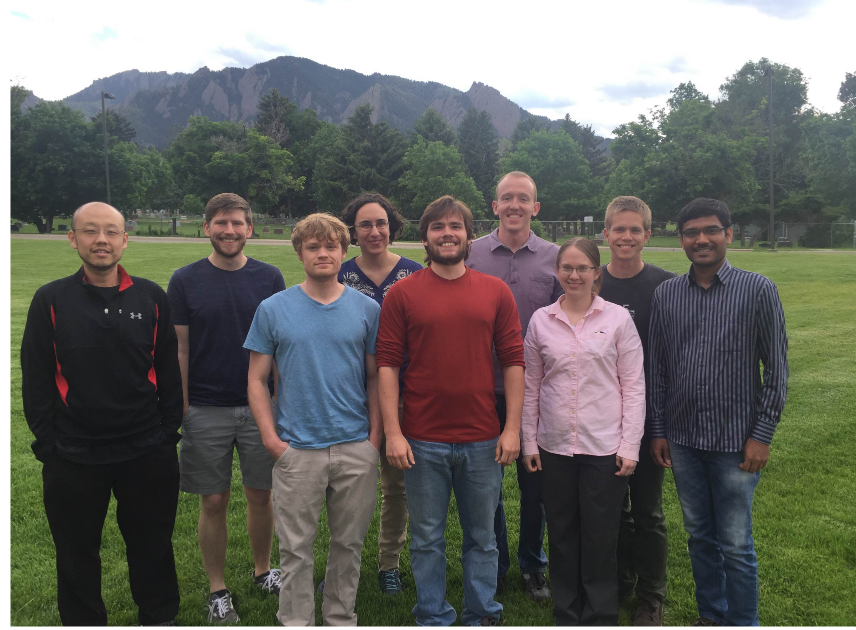
Postdocs: Fred Baynes, Katja Beha, Travis Briles, Aurélien Coillet, Josue Davila-Rodriguez, Pascal Del'Haye, Tara Drake, Dan Hickstein, Andrew Klose, Erin Lamb, William Loh, Antoine Rolland, Daryl Spencer, Gabriel Ycas

Visitors: Yi-Chen Chuang, Flavio Cruz, Lorenzo Hernandez, Francisco Senna, Chaitanya Sudapalli

Collaborators: John Bowers (UCSB), Joe Campbell (Virginia), Kartik Srinivasan (NIST Gaithersburg), Kerry Vahala (Caltech)





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NIST

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