Armani Lab @USC

Novel Material Platforms for Resonator Kerr Combs

Prof. Andrea Armani

USC Viterbi School of Engineering

@ArmaniResearchLab @ArmaniLab armanilab

Statement on picture taking

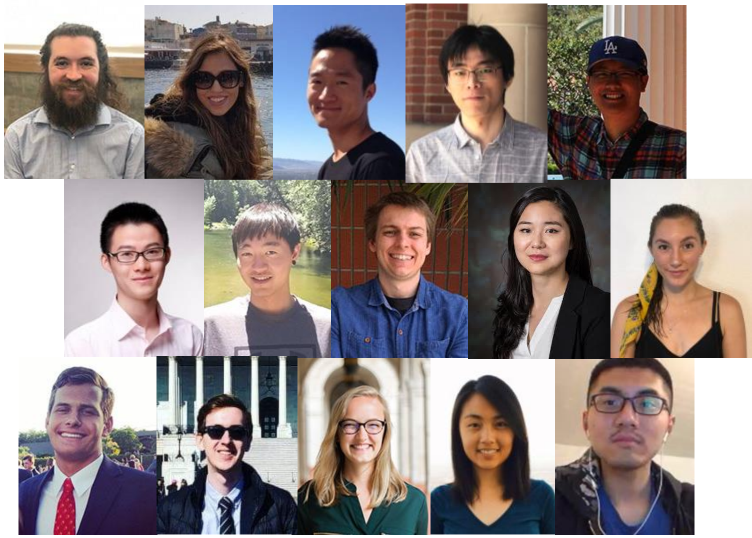
A PDF will be posted at:

http://armani.usc.edu

Therefore, while taking pictures is okay, you should also feel free to pay attention!

Acknowledgements

Post-docs/Graduate Students



Undergrad Students

Friends who shared slides

- Scott Diddams (NIST)
- Michal Lipson (Columbia)
- Andrey Matsko (OEWaves)
- Kartik Srinivasan (NIST)
- Myoung-Gyun Suh (Caltech)

More info

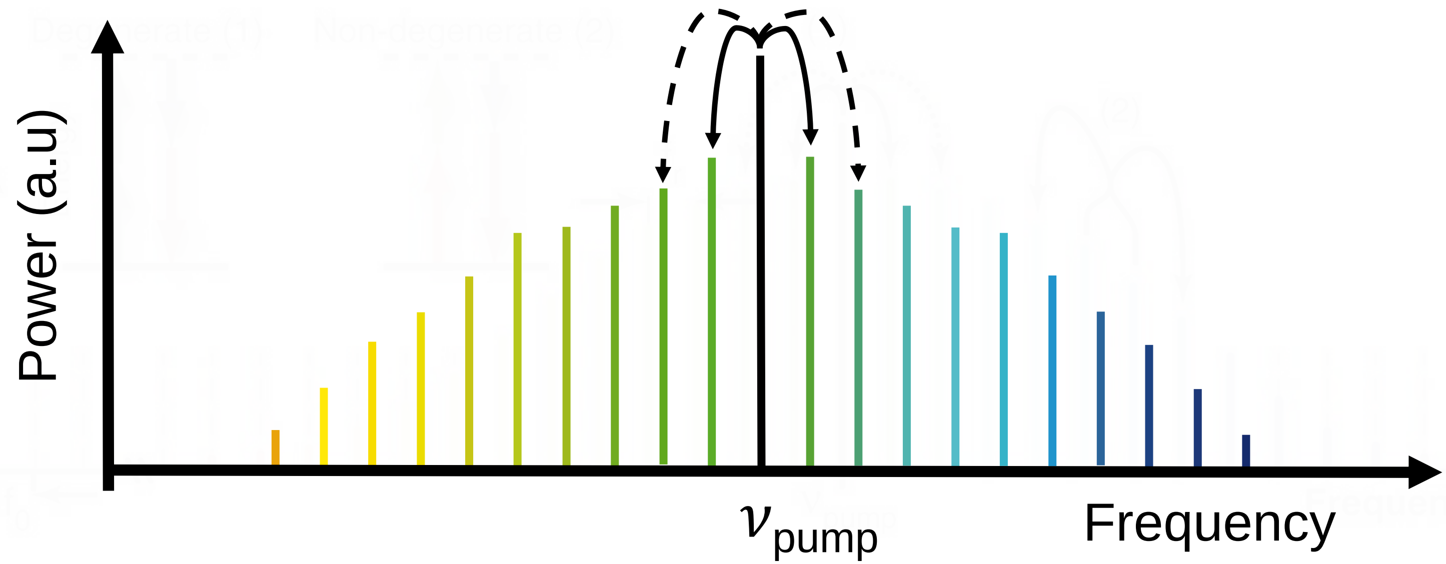
- http://armani.usc.edu
- @ArmaniLab
- @ArmaniResearchLab
- armanilab

Overview

- **(Brief) Background on frequency combs**
- **Whispering gallery mode cavity combs**
  - *Landmark demonstrations*
  - *Emerging material systems*
  - *Multi-material/multi-device platforms*
  - *Challenges and approaches being pursued*
- **Conclusions**

Optical Frequency Combs

A comb converts a single laser source into symmetrically and equally spaced emission lines (f_r) at higher and lower wavelengths.

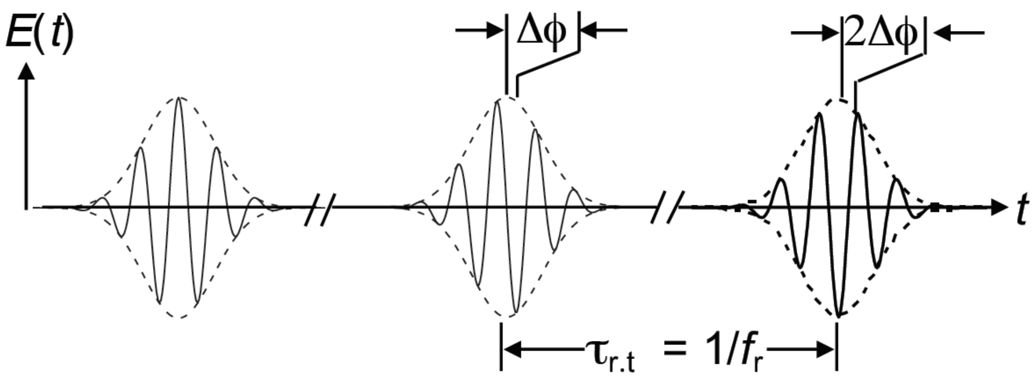


Limits:

- *Pump laser stability*
- *Comb spacing uniformity*

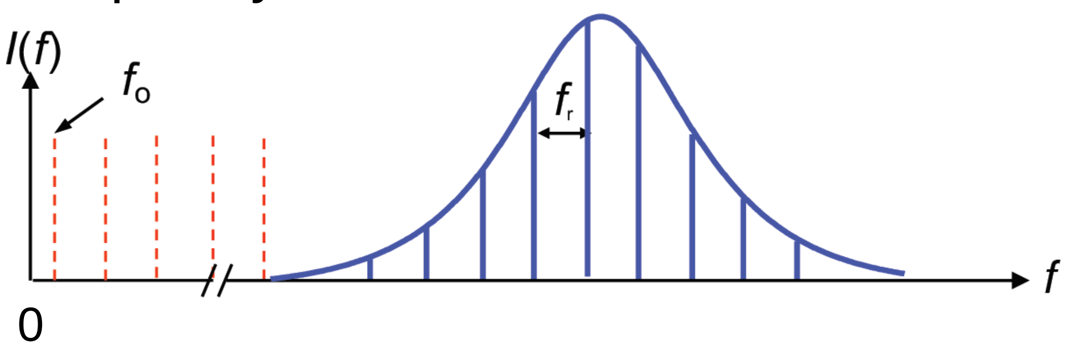
Optical Frequency Comb Generation

Time domain



$\phi = \Delta\phi(t/\tau) + \phi_o$ $\Delta\phi = 2\pi f_o / f_r$

Frequency domain



Challenge:

- Time domain: Phase evolves from pulse to pulse by $\Delta\phi$, and ϕ_o is unknown
- Frequency domain: Phase evolution impacts precision

Figure from: D. Jones, S. Diddans, J. Ranka, A. Stentz, R. Windeler, J. Hall, S. Cundiff, Science 288 (2000)

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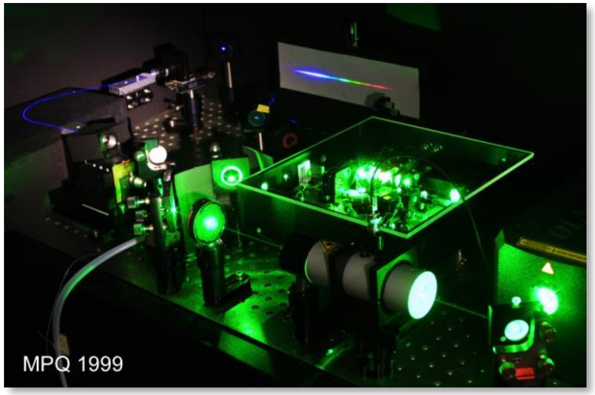
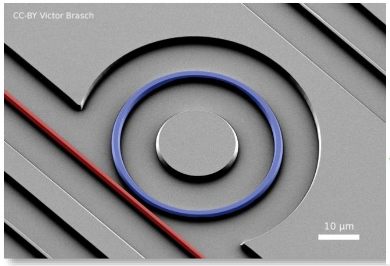
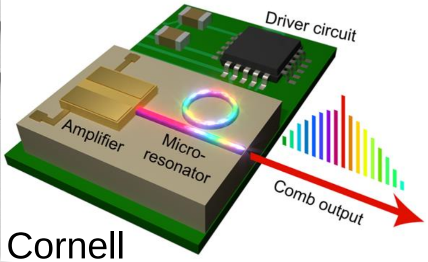
Moving from Laboratory Scale to Chip Scale



Addressing SWaP





Cornell

- Pulsed lasers (e.g. fs lasers)
- Fiber lasers (doped, structured fiber

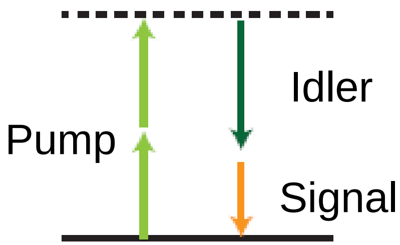
Generation principle of microcombs:
Kerr parametric oscillation

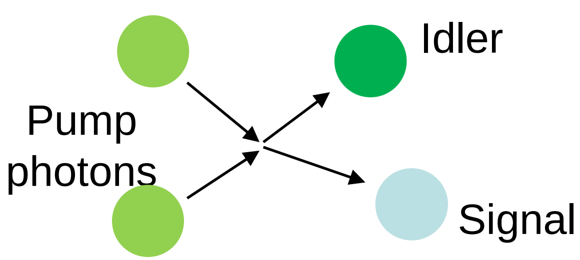
In materials, the electric polarization (P) depends on the electric field (E).

$$P_i = \varepsilon_0 \sum_{j=1}^{3} \chi_{ij}^{(1)} E_j + \varepsilon_0 \sum_{j=1}^{3} \sum_{k=1}^{3} \chi_{ijk}^{(2)} E_j E_k + \varepsilon_0 \sum_{j=1}^{3} \sum_{k=1}^{3} \sum_{l=1}^{3} \chi_{ijkl}^{(3)} E_j E_k E_l + \cdots$$

Kerr - nonlinearity

Kerr parametric oscillation





Basic requirements:

- High $\chi^{(3)}$
- Large number of pump photons

Cavity-based combs

Other considerations:

- f_r: device free spectral range (FSR)
- Comb span: dispersion, efficiency of four wave mixing (FWM) process

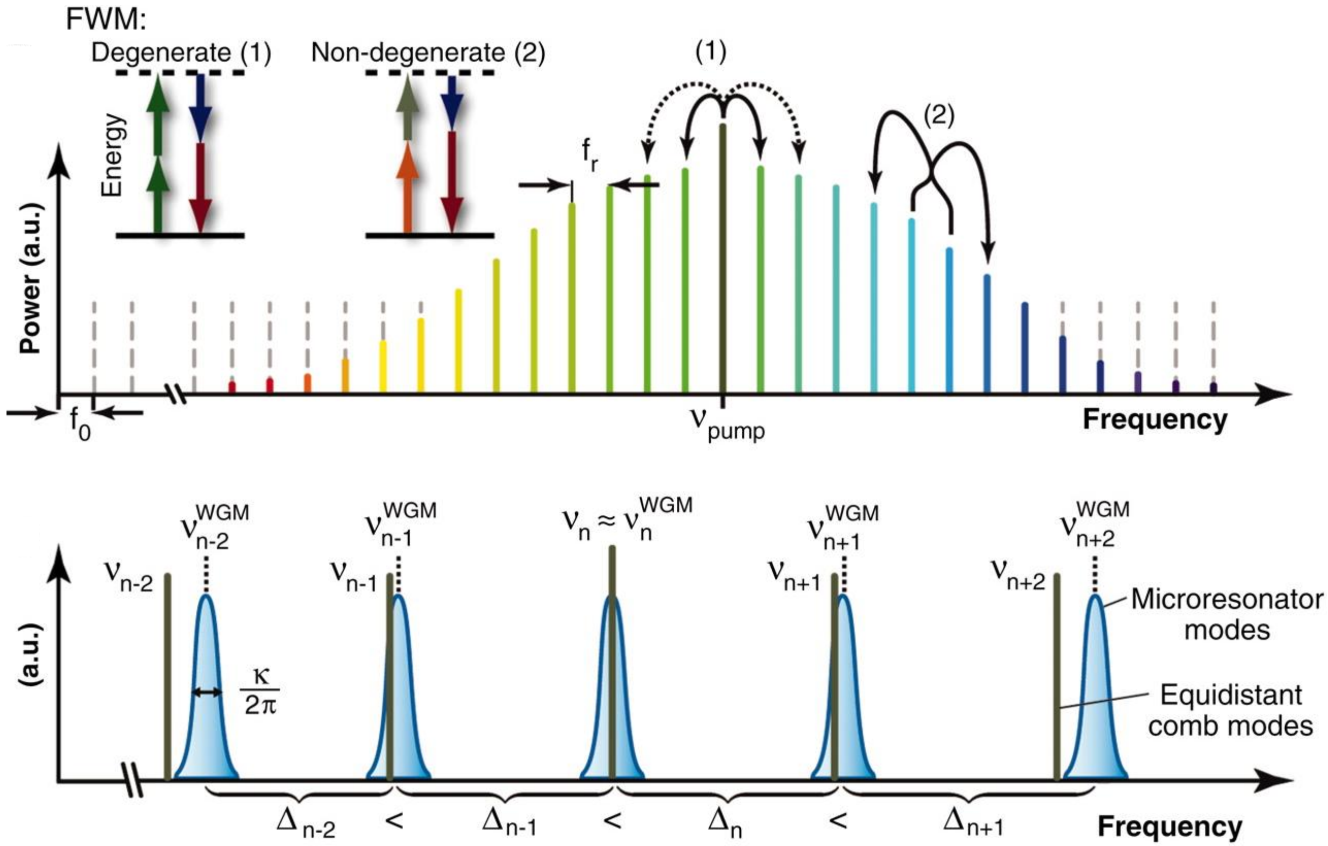
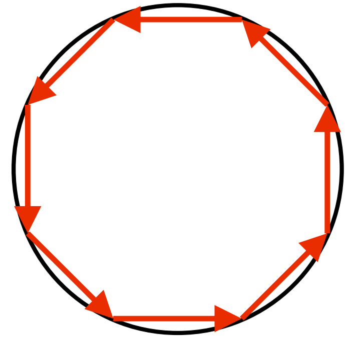


Figure from: T. Kippenberg, R. Holzwarth, S. Diddams, Science 332 (2011).

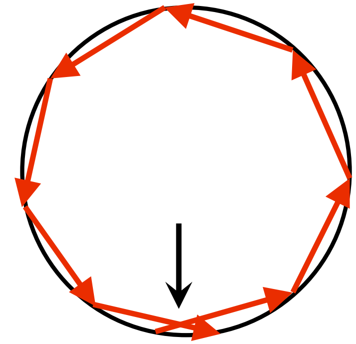
Whispering gallery in optics

St. Paul's Cathedral Whispering Gallery

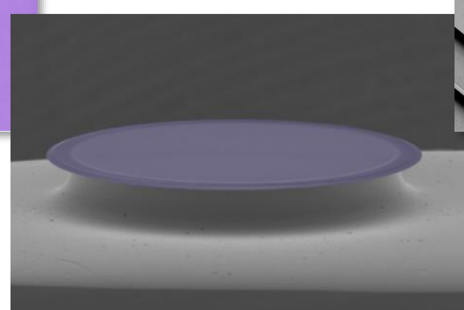
Geometric optics

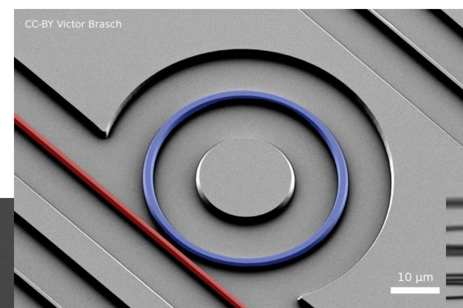


Integral (on-resonance)



Non-Integral (off-resonance)





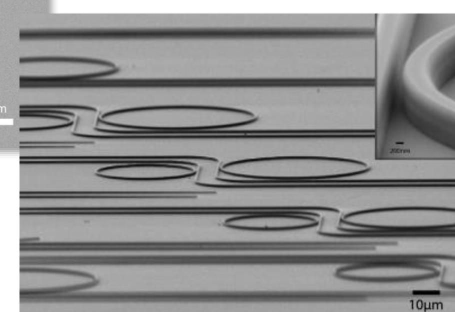


Photo by Matt Biddulph

OEWaves, Caltech, Cornell, Harvard

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Whispering gallery mode devices

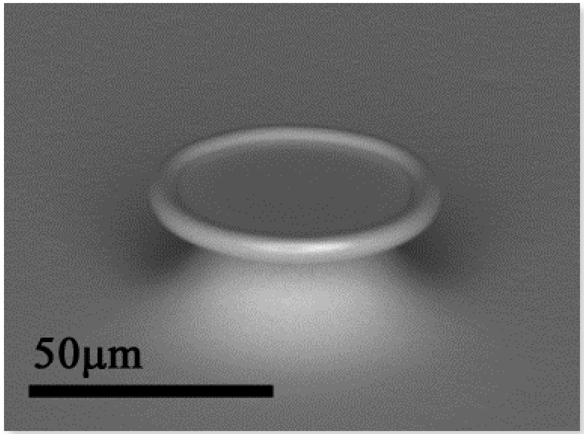


Figure of merit for resonators is quality factor (Q):

$Q=\lambda/\Delta\lambda$

λ=resonant wavelength
$\Delta\lambda$=FWHM of resonance

$$Q_{tot}^{-1} = Q_{mat}^{-1} + Q_{ss}^{-1} + Q_{rad}^{-1} + Q_{cont}^{-1} + Q_{coup}^{-1}$$

$$= Q_{in}^{-1} + Q_{ext}^{-1}$$

Q_{in} = intrinsic Q

- $1/Q_{mat}$ = loss due to material loss
- $1/Q_{ss}$ = loss due to surface roughness
- $1/Q_{rad}$ = bending loss, minimized by optimized size of resonant cavity
- $1/Q_{cont}$ = contamination loss, minimized by keeping cavity "clean"

Q_{ext} = extrinsic Q

- $1/Q_{coup}$ = coupling loss due to inefficient optical power transfer

Whispering gallery mode devices

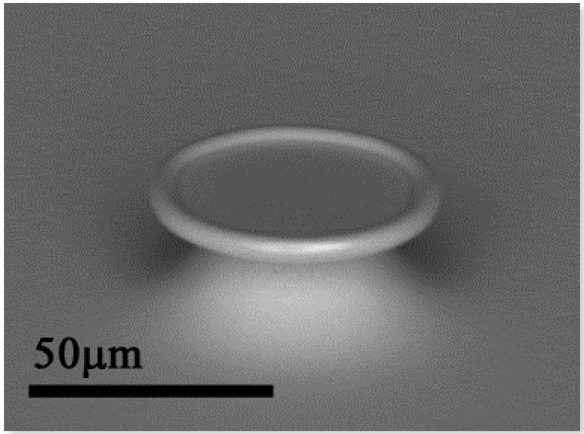


Figure of merit for resonators is quality factor (Q):

Q=λ/Δλ

λ=resonant wavelength
Δλ=FWHM of resonance

Benefit of resonators:

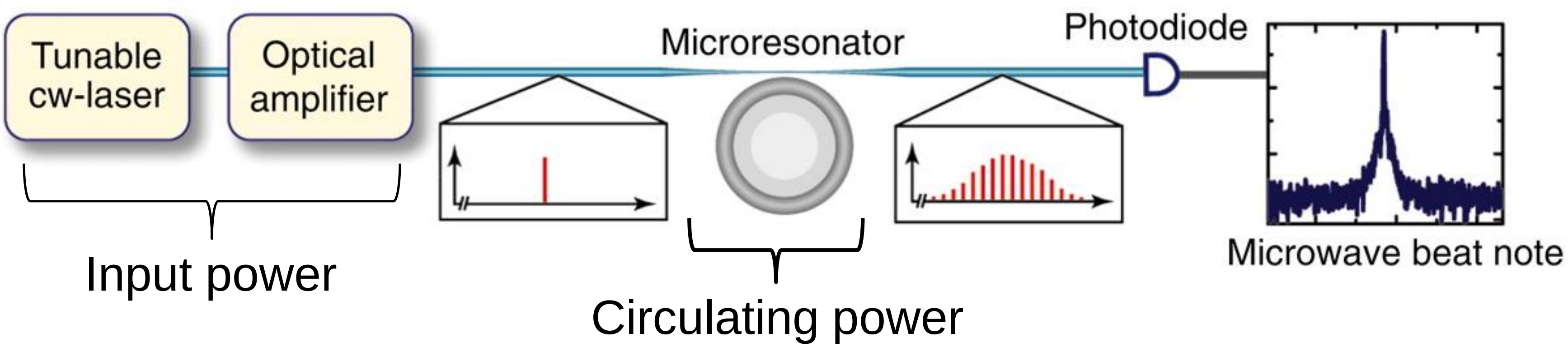
$$\frac{P_{circ}}{P_{input}} = \frac{1}{2\pi}\frac{\lambda Q}{\pi n D} = \frac{1}{2\pi}F$$

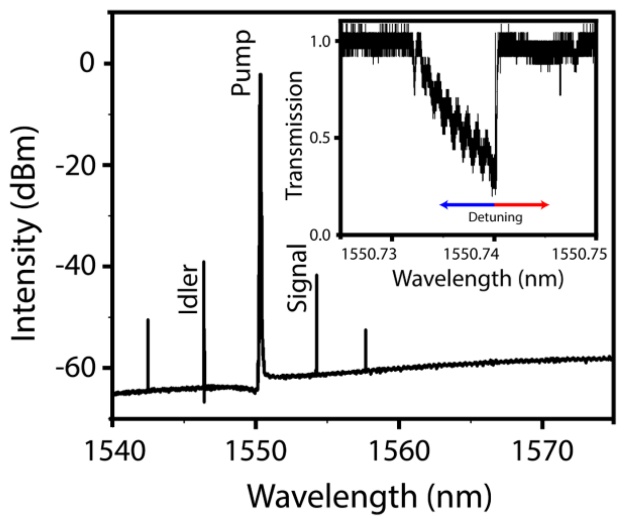
$$I_{circ} = \frac{P_{circ}}{A} = \frac{\lambda}{2\pi}\frac{Q}{V}P_{input}$$

P_{circ}=circulating power
D=diameter
I_{circ}=circulating intensity
V=mode volume

P_{input}=input power
F=Finesse
A=mode area

Cavity-based combs





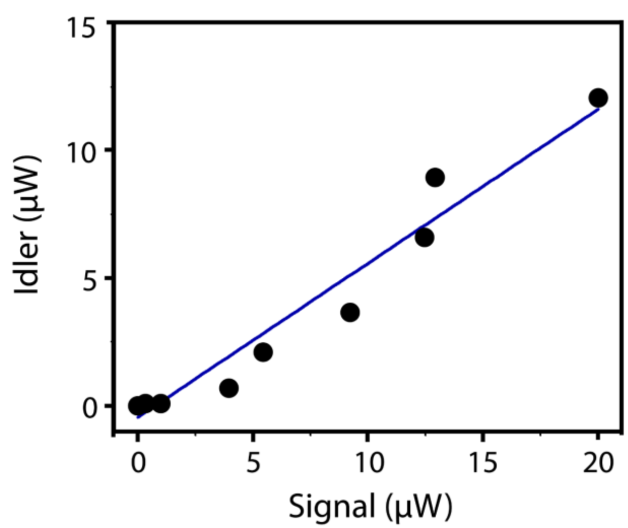
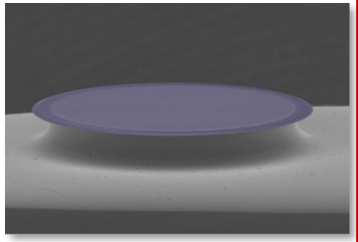


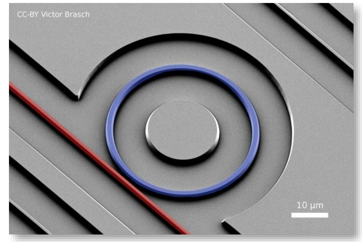
Figure from: T. Kippenberg, R. Holzwarth, S. Diddams, Science 332 (2011).
Castro-Beltran, R., … Armani, A. M., **4** (11) 2828 ACS Photonics (2017).

Cavities for combs

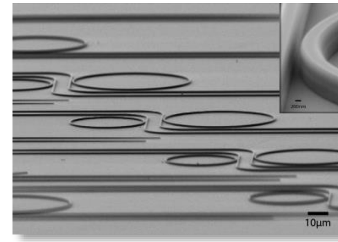
Fluorides



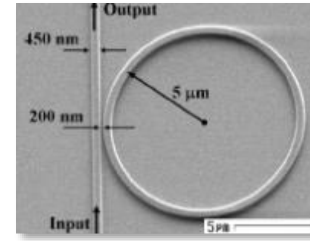
Oxides



Nitrides



Diamond



Silicon

Goals:

- High circulating intensity
- Precise mode spacing over large wavelength range
- Integrated, packaged system

Approaches:

- High Q, small V (high F)
- Large diameter (FSR, dispersion)
- Low, controllable material/geometric dispersion
- Designing for packaging

Loncar (Harvard), Bowen (Queensland), Yang (Wash U), Vahala (Caltech), Lipson (Columbia), Kippenberg (EPFL), Xiao (Peking), Vollmer (Exeter), Barclay (Calgary), Poon (HKU), Keller (ETH), …
OEWaves, JPL, NIST, Northrop Grumman

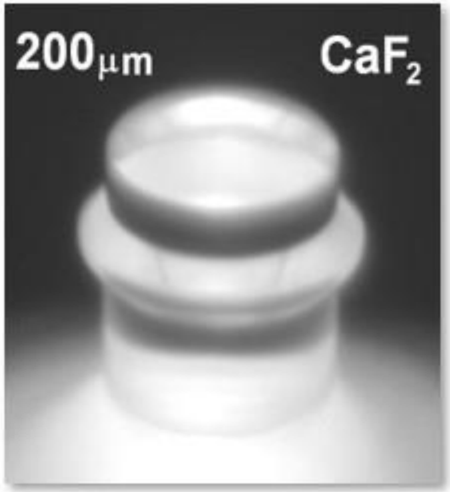
Crystalline resonator fabrication

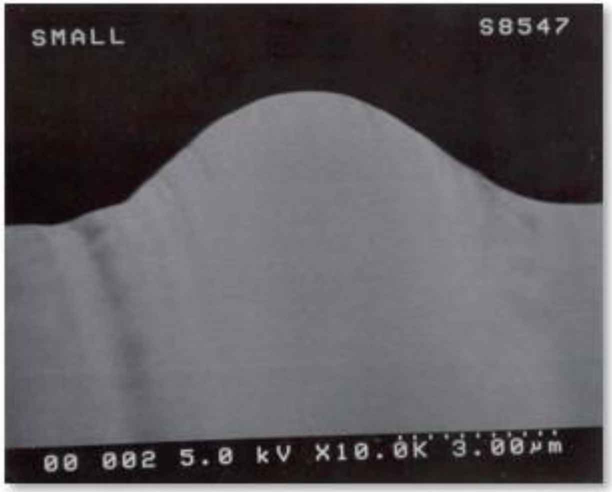
Diamond turning and other techniques

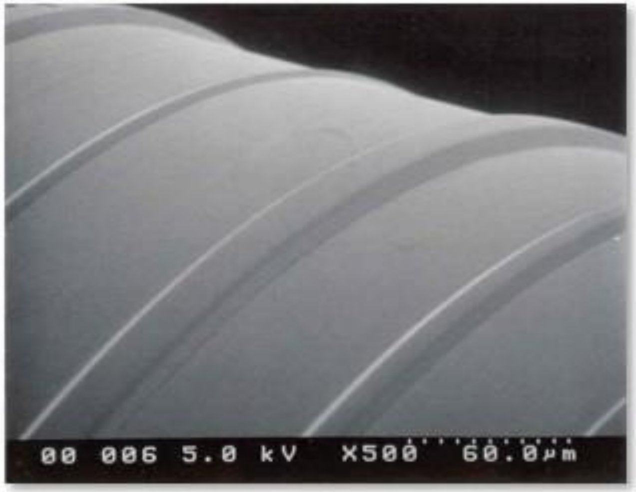
Microresonators

Single mode resonators

Coupled resonators



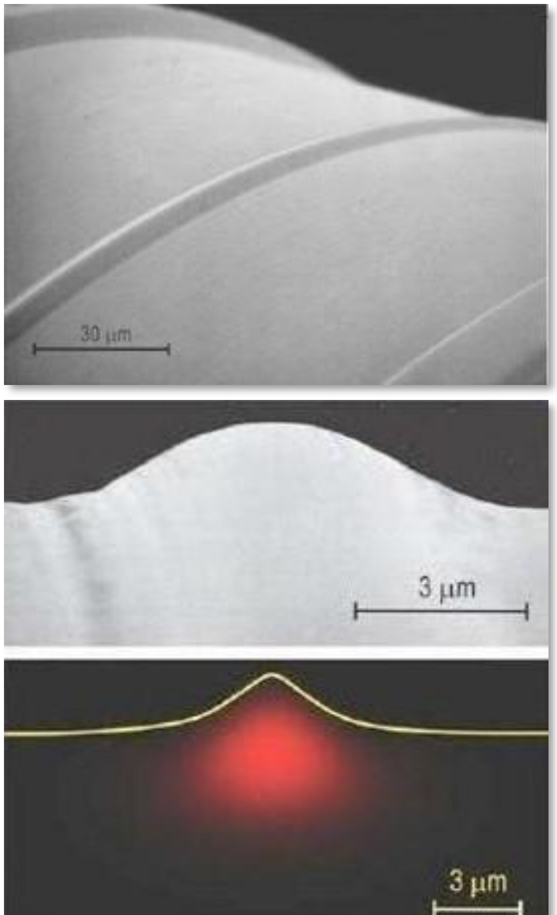


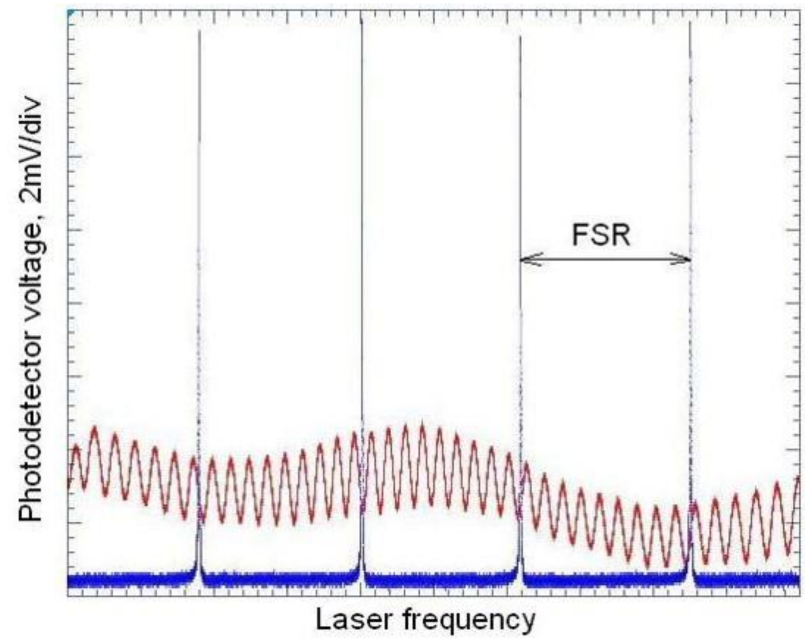


I.S. Grudinin, A.B. Matsko, A.A. Savchenkov, D. Strekalov, V. Ilchenko and Lute Maleki, Optics Communications, **265**, 33-38 (2006).

CaF_2 microcavity

Extremely clean broadband spectrum with record Q's (>10^{10} routinely)

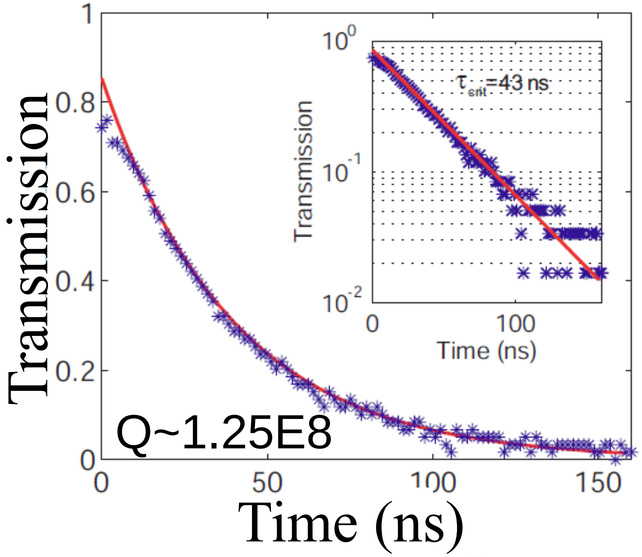


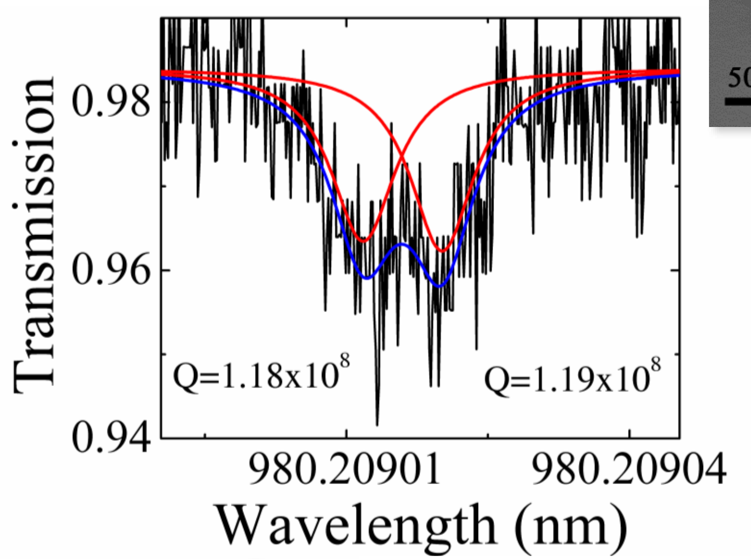


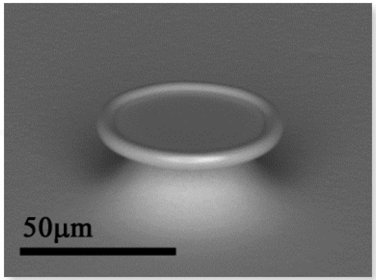
Single mode CaF_2 resonator

A.A. Savchenkov, I.S. Grudinin, A.B. Matsko, D. Strekalov, M. Mohageg, V.S. Ilchenko and Lute Maleki. Optics Letters, **31**, 1313-1315 (2006).

Silica toroidal cavities

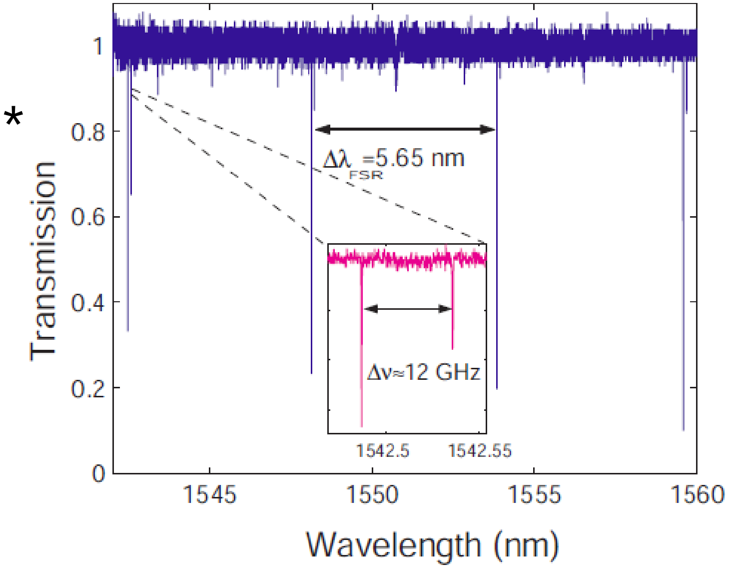






Q measured two ways: linewidth and ringdown*

Well-defined spectrum (ideal for combs), if small diameter toroid is used.



* Not same cavity. Shown to enable discussion of CW/CCW mode splitting and ringdown.

D. Armani, et al, Nature **421** (2003).
X. Zhang, et al, Applied Physics Letters **96** 15 (2010).

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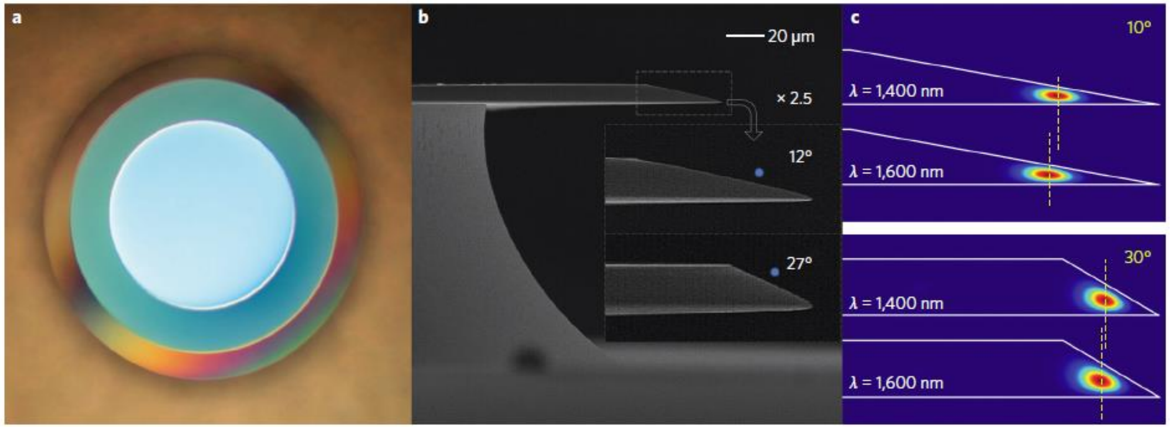
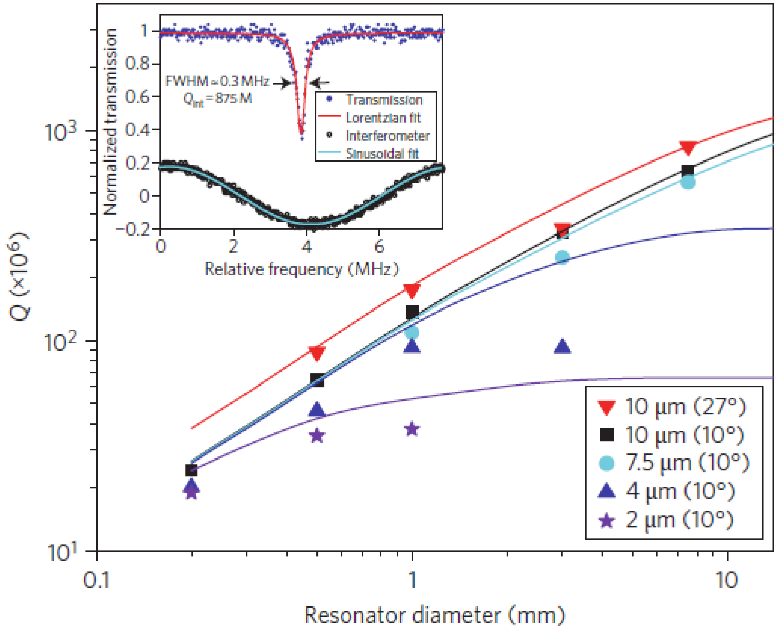
Silica microdisk cavities



Location and shape of optical mode changes with wedge angle

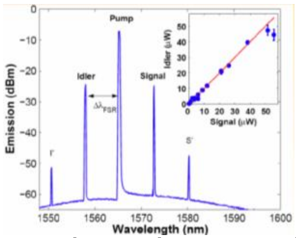


- Q is dominated by surface scattering
- Thicker oxides have higher Q factors

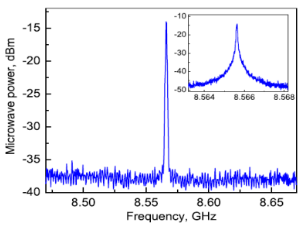
H. Lee et al, Nat Photonics, **6** 369-373 (2012).

Some Early Experiments

Hyper-parametric oscillation

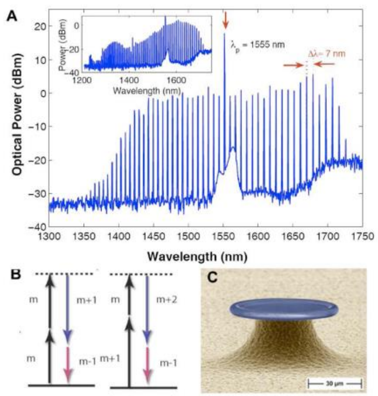


T. J. Kippenberg et al., Phys. Rev. Lett. **93**, 083904 (2004).



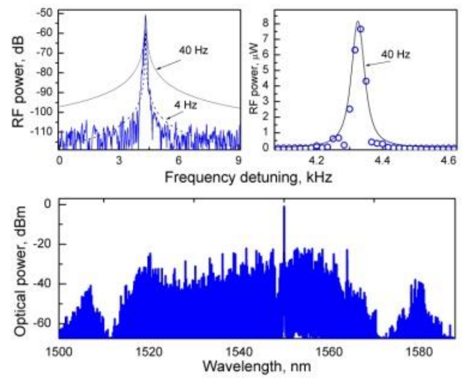
A. A. Savchenkov et al., Phys. Rev. Lett. **93**, 243905 (2004).

Kerr frequency comb



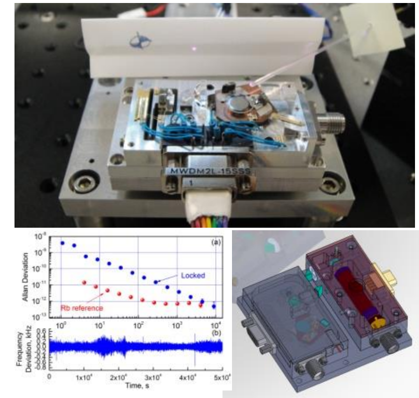
P. Del Haye, et al., Nature **450**, 1214 (2007)

RF photonic oscillator



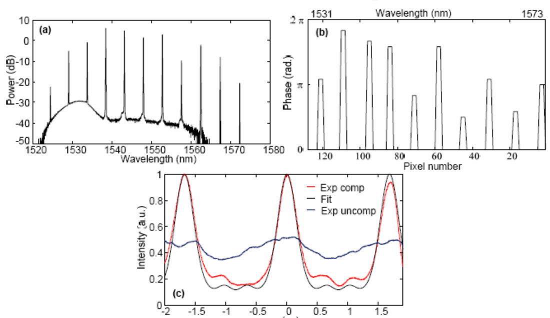
A. A. Savchenkov et al., Phys. Rev. Lett. 101, 093902 (2008)

Single point stabilization



A. A. Savchenkov et al., Opt. Lett. **38**, 2636 (2013)

Waveform manipulation



F. Ferdous et al., Nature Photonics **5**, 770 (2011)

On-chip fs pulse generation

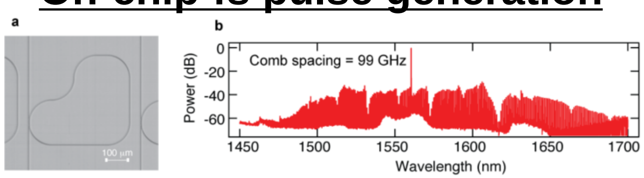
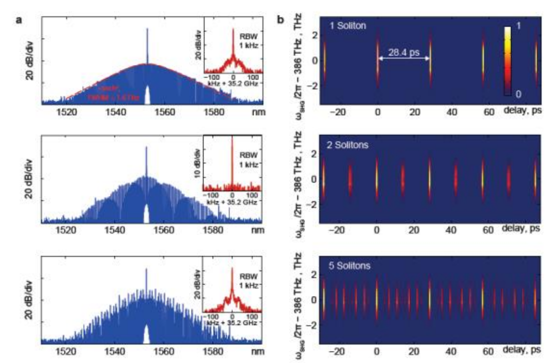


Fig. 1. (a) A scanning electron micrograph of a silicon-nitride millimeter-scale resonator coupled to a bus waveguide. (b) Optical

Fig. 2. (a) Filtered optical spectrum of a frequency comb with 99 GHz free spectral range. (b) Normalized autocorrelation trace of pulse train obtained from the comb after filtering 25 nm. The repetition rate of the pulses is 10.1 ps and the full-width at half maximum is 193 fs.

K. Saha et al, Opt. Express 21, 1335 (2013)

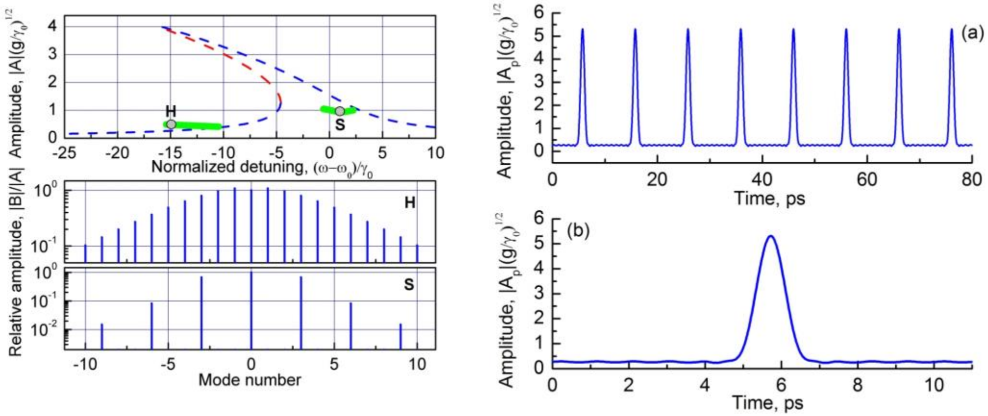
Soliton Kerr comb



T. Herr et al., Nature Photonics **8**,145–152 (2014)

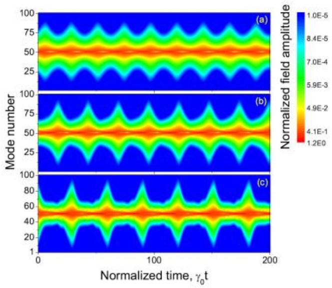
Major Regimes of Operation

Mode locking

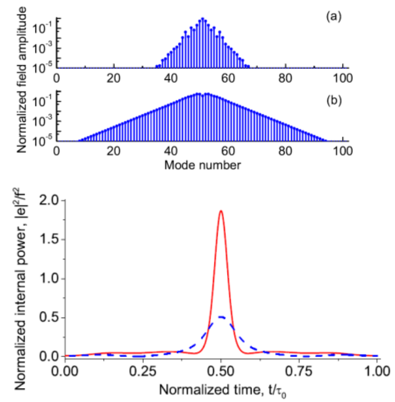


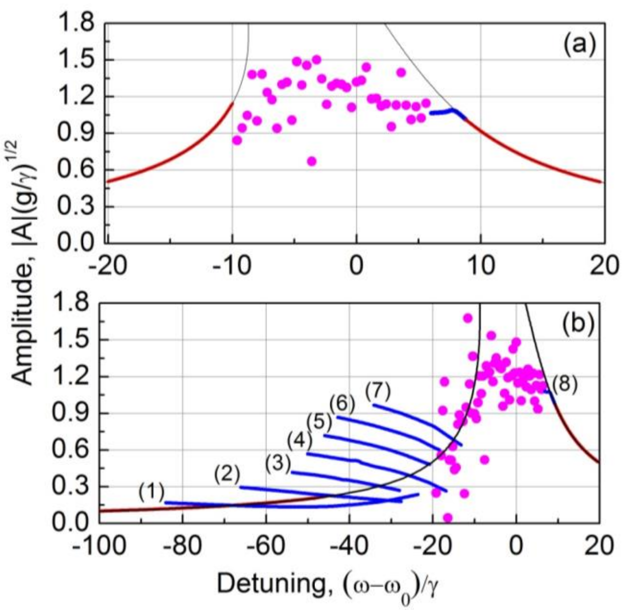
A. B. Matsko et al., Phys. Rev. A **85**, 023830 (2012)

Breathers

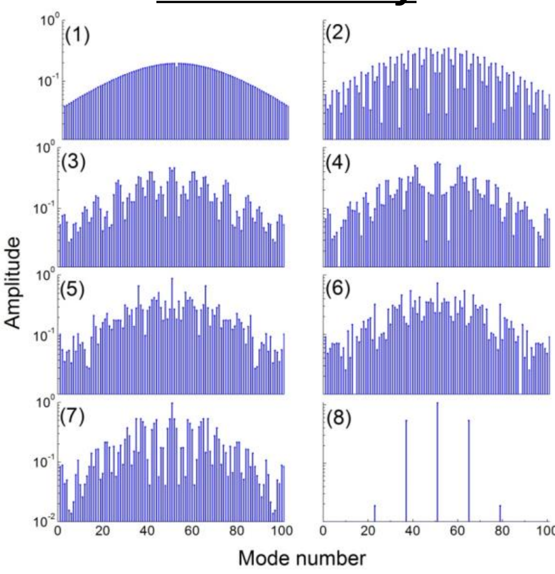


A. B. Matsko et al. Opt. Lett. **37**, 4856 (2012)

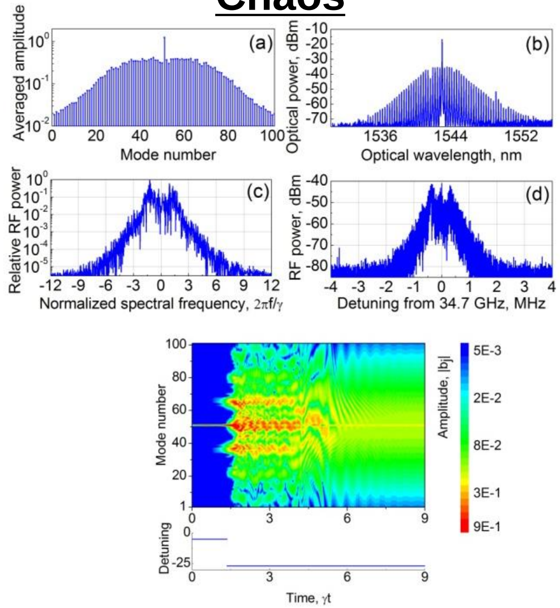




Multistability



Chaos



A. B. Matsko et al., Opt. Lett. **38**, 525 (2013)

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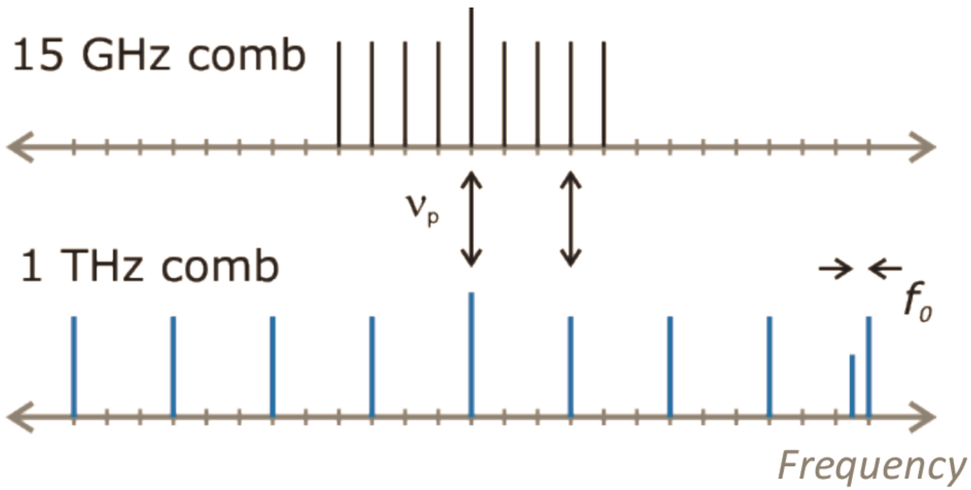
Going back to go forward

To enable potable combs, laser stability issue must to be solved:

⟶ Self-referencing is needed.

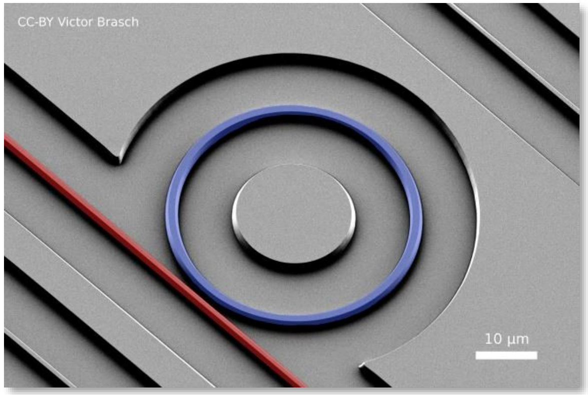
Challenges: power, frequency control, material properties, integration



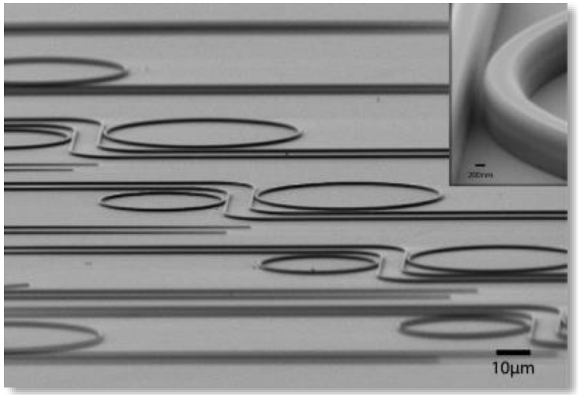
Solution: Expand comb toolbox to other material systems

Alternative and emerging material systems

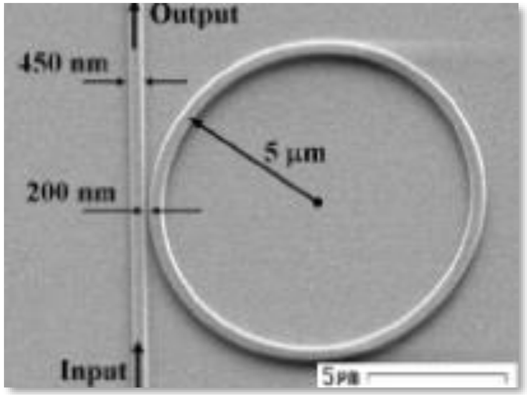
- Balance **<u>dispersion</u>** (geometric, material) with nonlinear behaviors and loss
- Address packaging
- Expand wavelength range (UV? Mid-IR?)



SiN



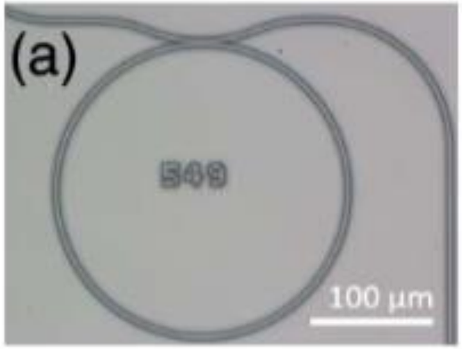
Diamond



Silicon

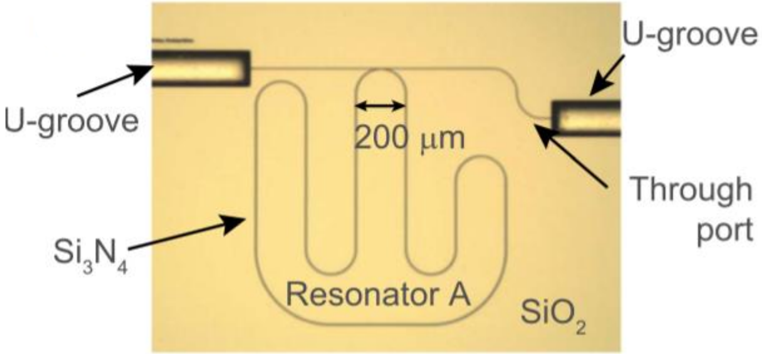
Silicon Nitride (Si_3N_4) microcavities

Microring



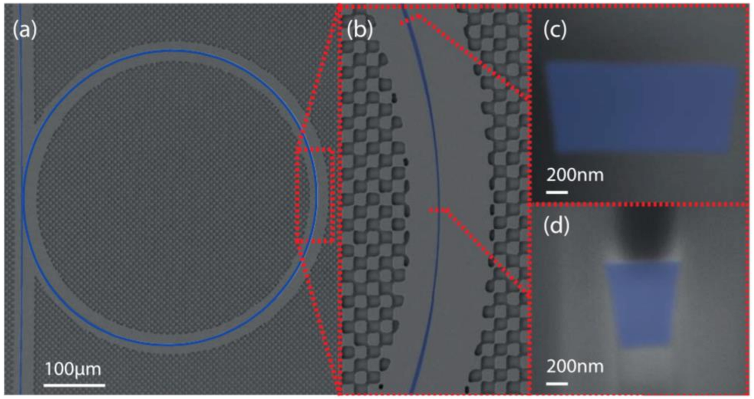
X. Ji…A. Gaeta, M. Lipson, Optica, 4, 6, 2017

Finger-shaped racetracks



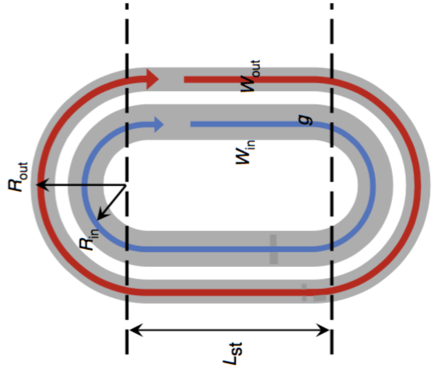
Y. Xuan…A. Weiner, M. Qi, Optica, 3, 11, 2016

Tapered rings for suppressing higher order modes



A. Kordts…T. J. Kippenberg, Optics Letters, 41, 3, 2016; S.-W. Huang… C. Wong, Scientific Reports, 6, 26255, 2016

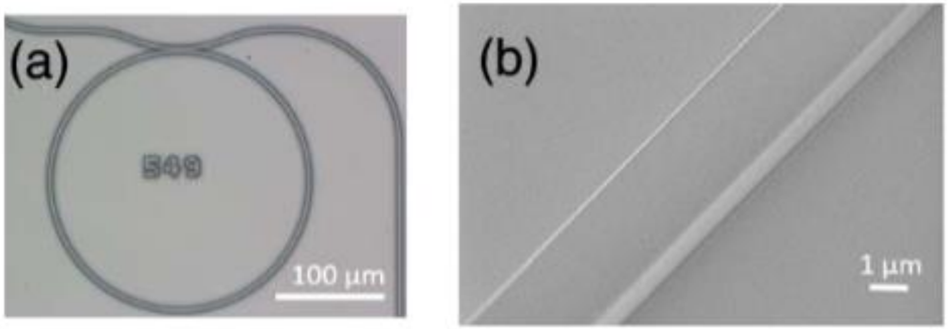
Concentric resonators for dispersion engineering



S. Kim…A. Weiner, M. Qi, Nature Communications, 8, 1, 2017.

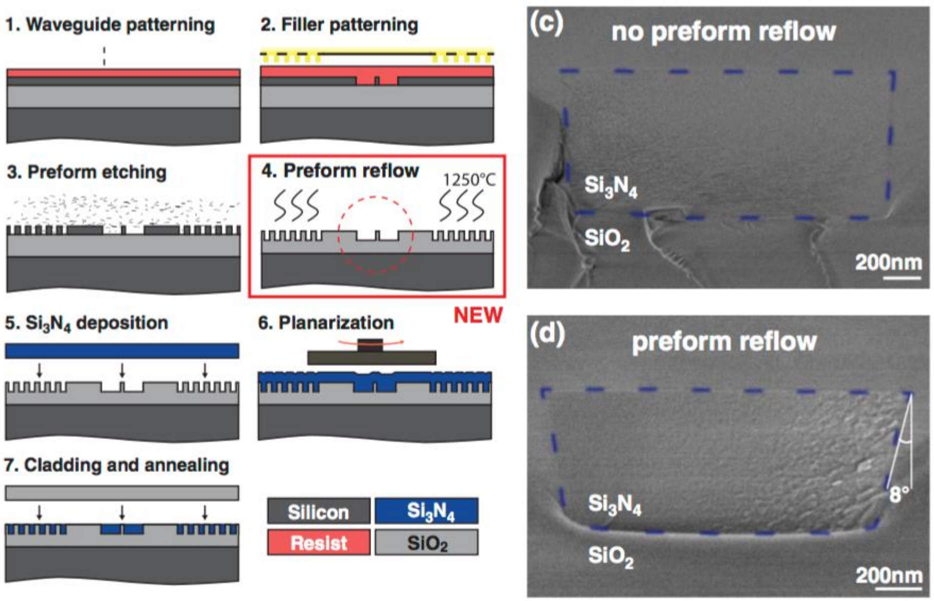
Silicon Nitride (Si_3N_4) microcavities

- Reduce surface roughness by improving etching receipts, polishing top surface and improve lithography. Up to 37 million Q was achieved for a 2.5 um width ring.



X. Ji…A. Gaeta, M. Lipson, Optica, 4, 6, 2017

- Damascene reflow process to smooth the surface and reduce scattering loss. Mean Q in excess of 5 million are obtained.

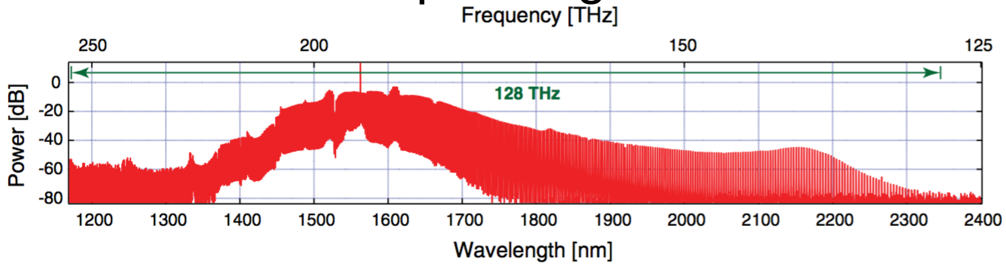


M. H. P. Pfeiffer…T. J. Kippenberg, Optica, 5, 7, 2018

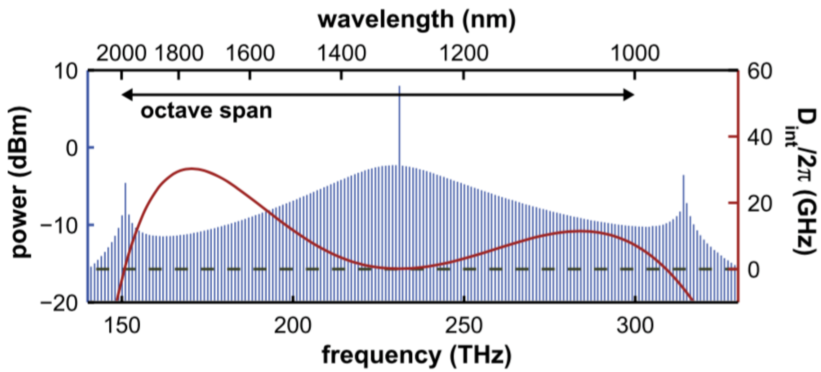
Silicon Nitride (Si_3N_4) Combs

Dispersion of the Si_3N_4 rings can be engineered by changing the width and height to achieve:

Octave spanning combs

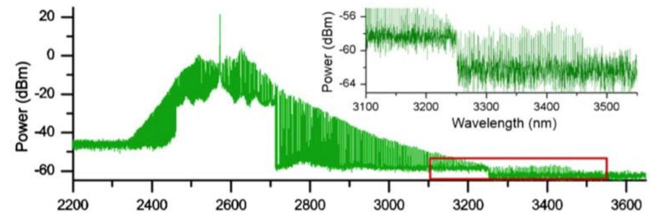


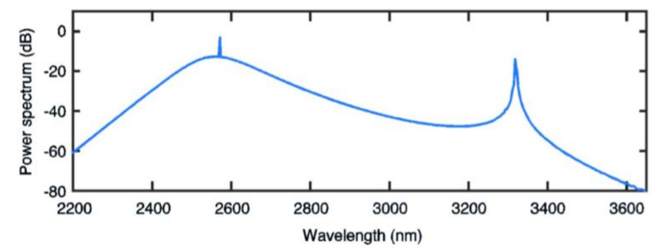
Y. Okawachi,…M. Lipson, A. L. Gaeta, Optics Letters, 36, 17, 2011



M. H. P. Pfeiffer…T. J. Kippenberg, Optica, 4, 7, 2017

Mid-IR combs



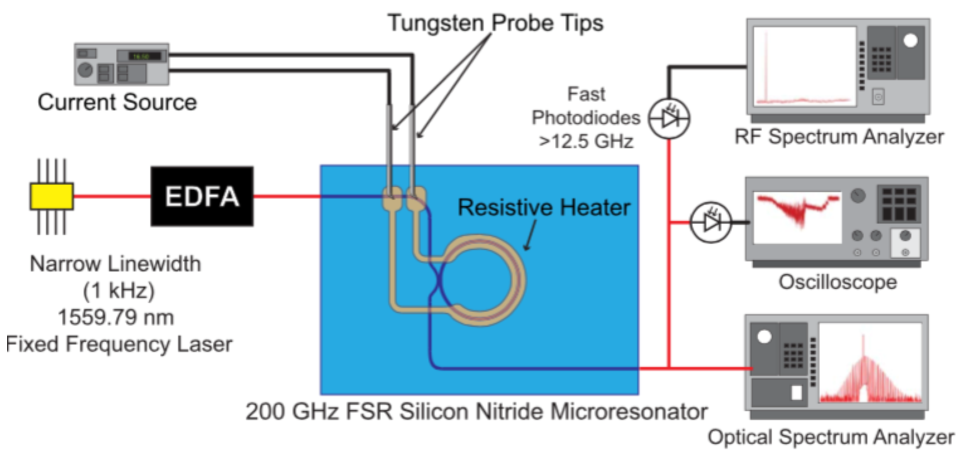


K. Luke,…M. Lipson, Optics Letters, 40, 21, 2015

Silicon Nitride (Si_3N_4) Combs

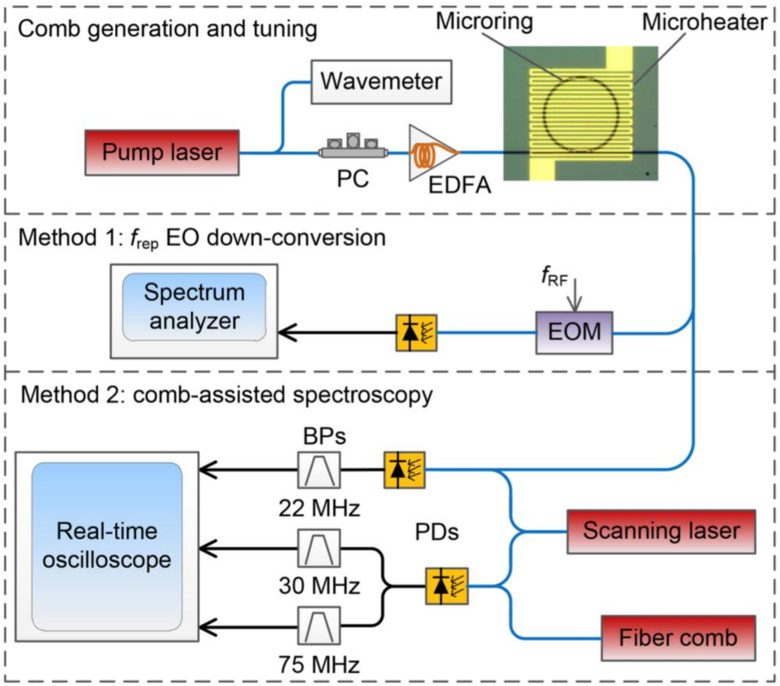
Moving past passive systems:

Mode locking with integrated heaters



C. Joshi,…M. Lipson, A. Gaeta, Optics Letters, 41, 11, 2016

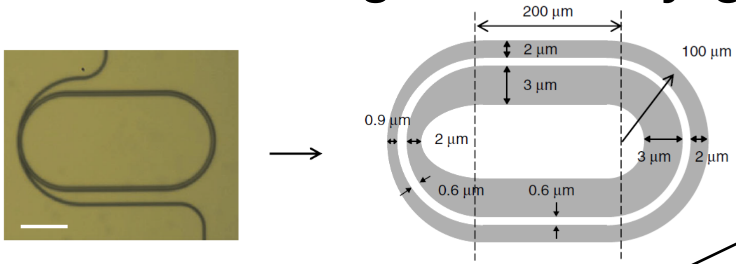
Tuning line spacing and central spacing

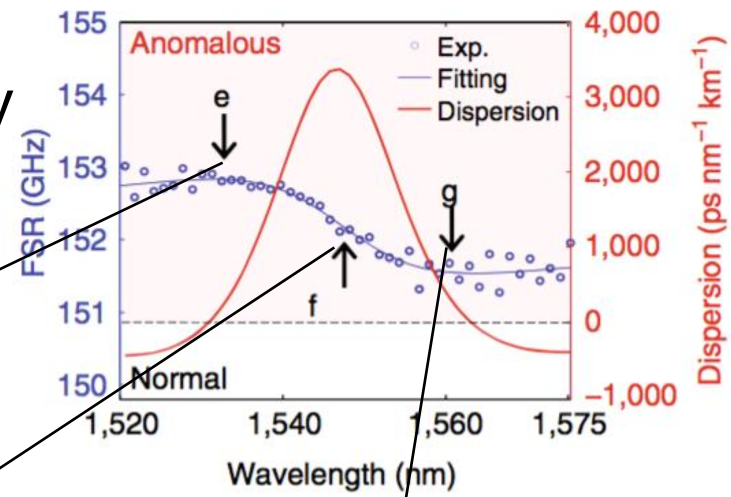


X. Xue…A. M. Weiner, Optics Express, 24, 1, 2016

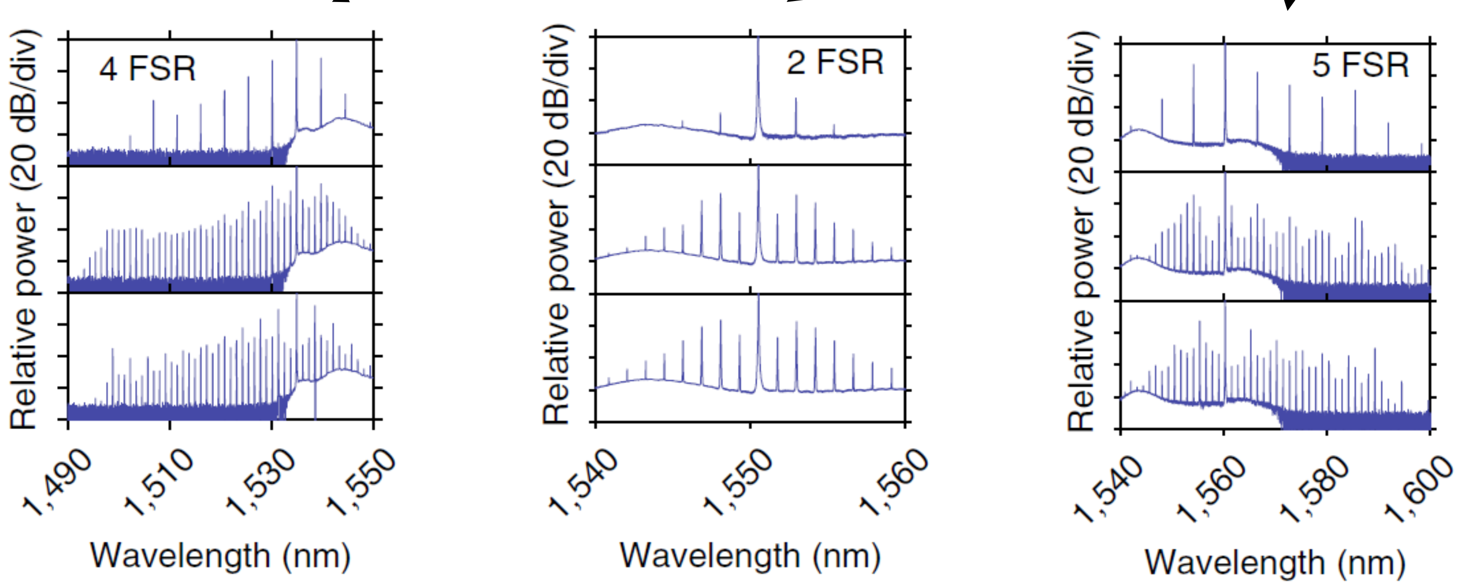
Dispersion engineering via geometry

Dispersion of the Si_3N_4 resonators can also be engineered by geometry





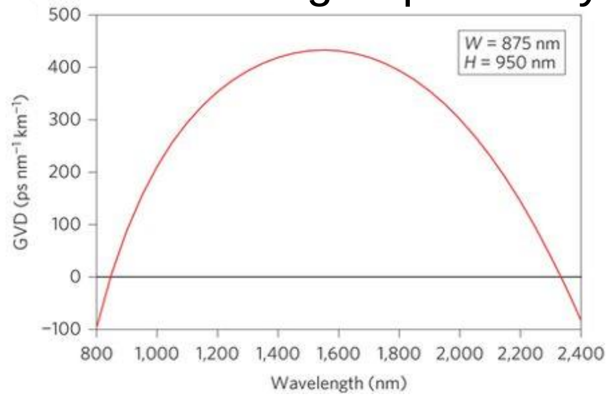
Tune the pump laser

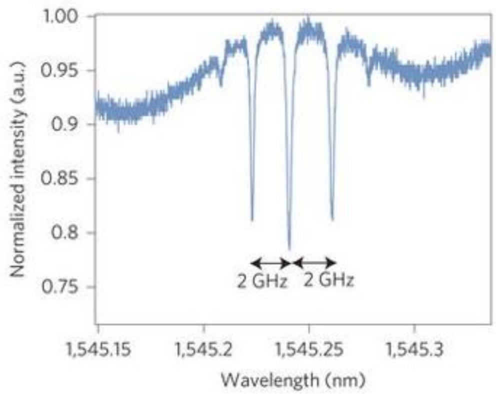


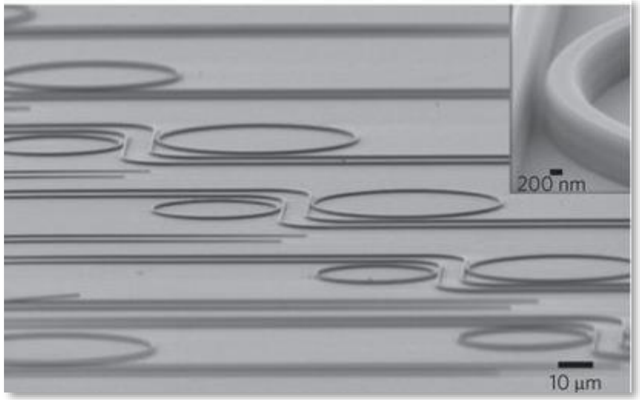
S. Kim…A. Weiner, M. Qi, Nature Communications, 8, 1, 2017

Diamond microring cavity

- High nonlinear refractive index (n_2): 1.3 x 10^{-19} m^2/W
- Low absorption losses from UV to IR
- High thermal conductivity
- Lack of two-photon absorption due to its large bandgap of 5.5 eV
- Anomalous group velocity dispersion in near-IR







Micro-ring resonator

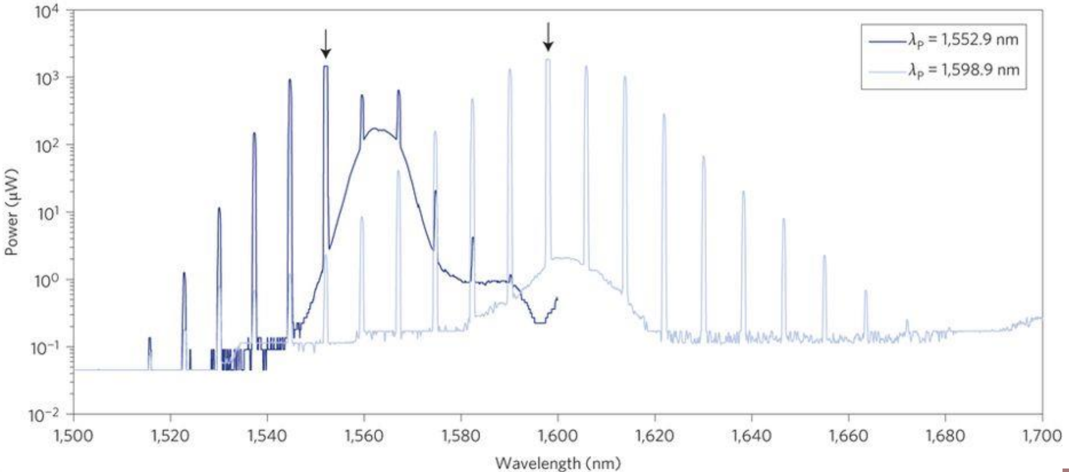
- Radius: ~ 30 μm
- Width: 875 nm
- Height: 850 nm

Q = 1.14 x 10^6

Span ~ 165 nm at 80 mW (1510 ~ 1675 nm)

FSR: 925 GHz

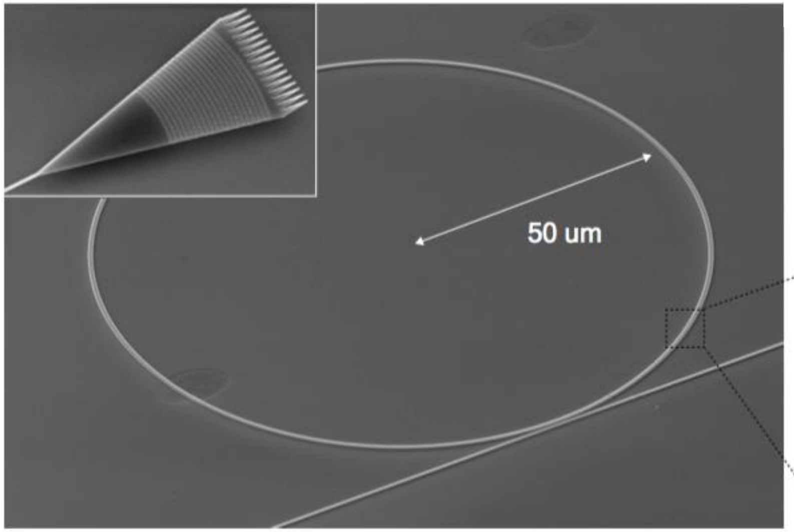
P_{th}=20mW

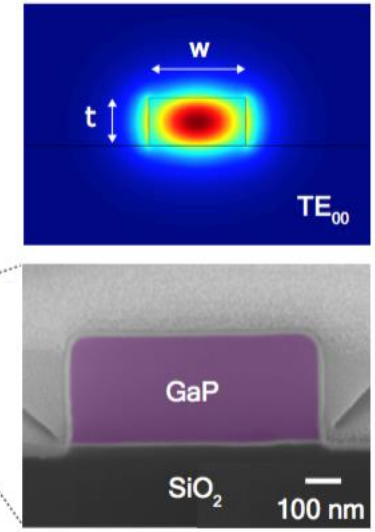


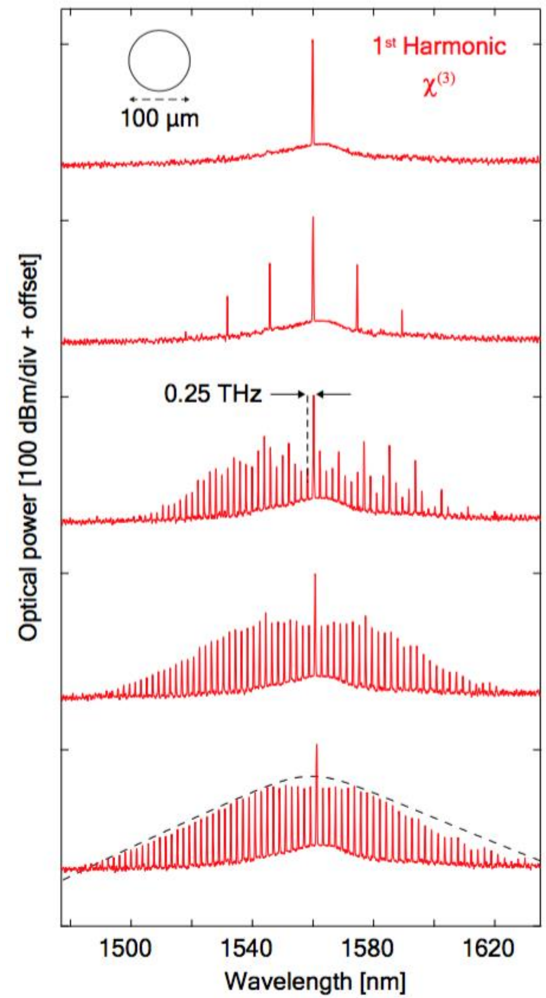
Higher coupling efficiency + better dispersion = more lines at longer pump wavelength

B. J. M. Hausmann, … and M. Loncar, *Nature Photonics,* **8,** 2014

Gallium Phosphide (GaP) microring







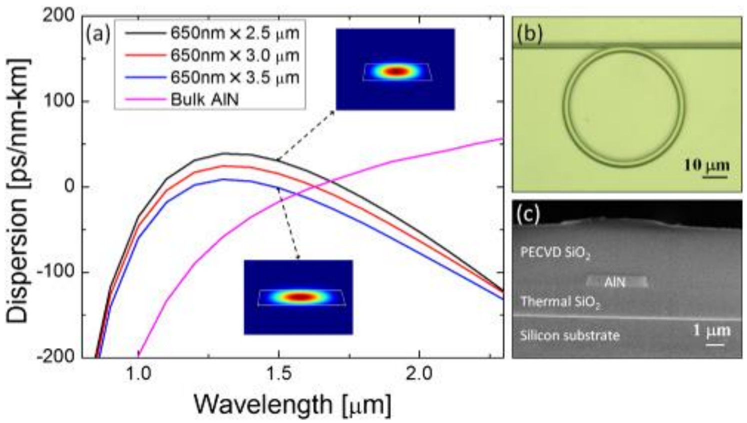
- $Q>10^5$
- High n_2 in telecom: 1.2×10^{-17} m^2/W
- Parametric threshold: 3 mW
- Span: >100 nm @ 100 mW

D. J. Wilson,…T. Kippenberg, P. Seidler, CLEO, SW3A.1, 2018
D. J. Wilson,…T. Kippenberg, P. Seidler, arXiv preprint arXiv:1808.03554, 2018

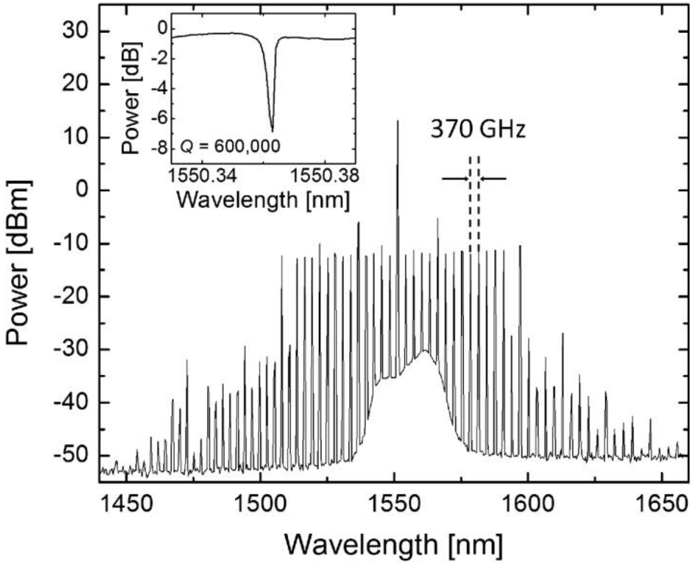
Aluminum Nitride resonator

- Noncentrosymmetric crystal structure: second- ($\chi^{(2)}$) *and* third-order ($\chi^{(3)}$) optical nonlinearities
- High nonlinear refractive index (n_2) value: 2.3 x 10^{-19} m^2/W
- Near zero group-velocity dispersion at near-IR region (~1550 nm)

Frequency comb with $\chi^{(3)}$



Q = 8 x 10^5
Span : ~ 200 nm at 500 mW (1450 ~ 1650 nm)
FSR: 370 GHz

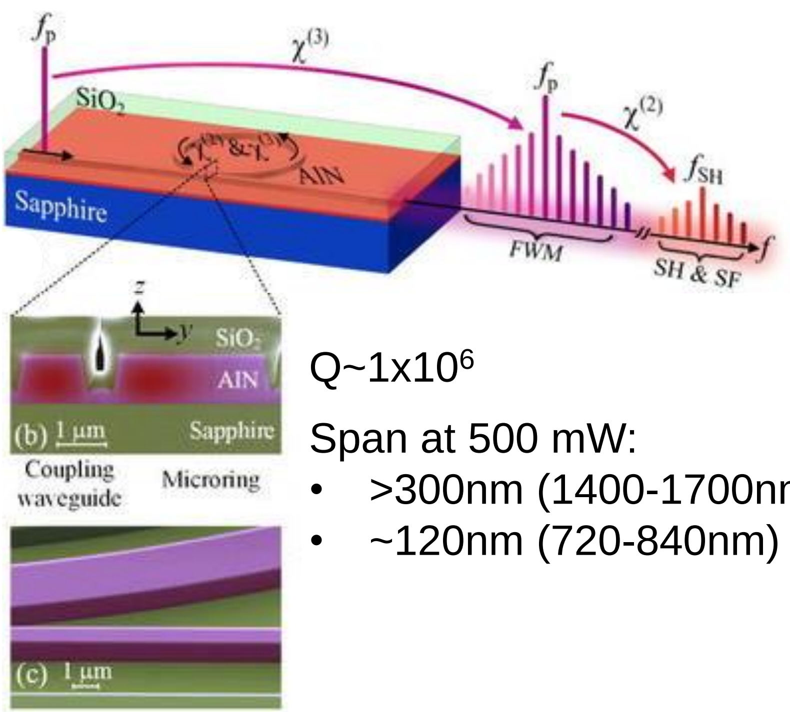


H. Jung, …, and H X. Tang, *Optics Letters,* 38, 15, 2013

Aluminum Nitride resonator

- Noncentrosymmetric crystal structure: second- ($\chi^{(2)}$) and third-order ($\chi^{(3)}$) optical nonlinearities
- High nonlinear refractive index (n_2) value: 2.3 x 10^{-19} m^2/W
- Near zero group-velocity dispersion at near-IR region (~1550 nm)

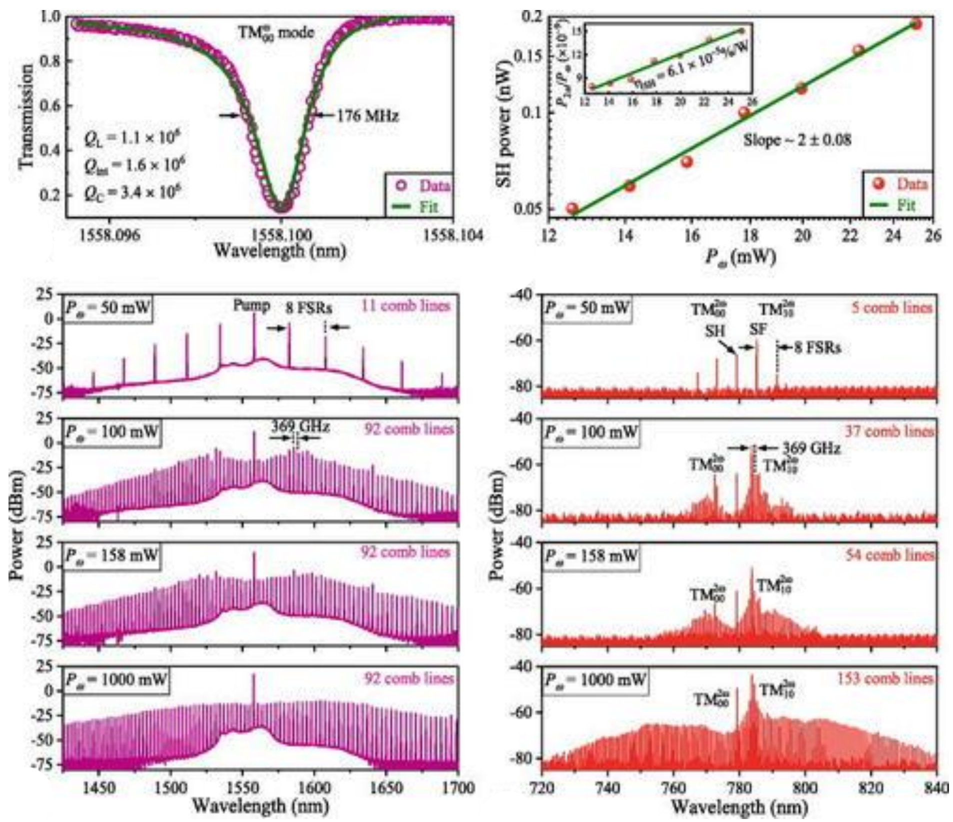
Frequency comb with both $\chi^{(2)}$ and $\chi^{(3)}$



Q~1x10^6

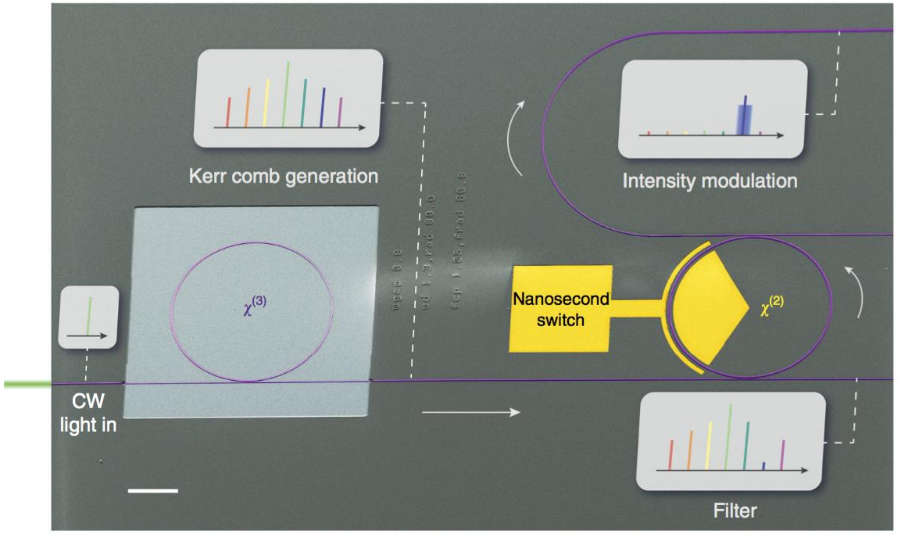
Span at 500 mW:

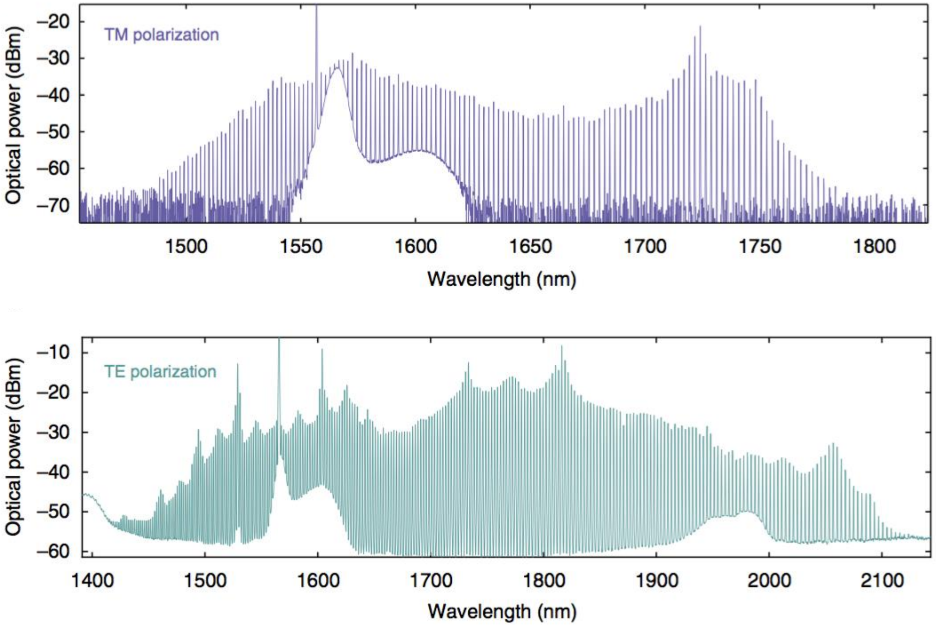
- >300nm (1400-1700nm)
- ~120nm (720-840nm)



X. Liu, C. Sun, … J. Wang, *Applied Physics Letters*, 113, 17, 2018

Lithium Niobate ($LiNbO_3$) cavities





- Q: 1.1×10^6
- n_2 : 1.8×10^{-19} m^2/W
- Parametric threshold: 80 mW
- Span: >700 nm @ 300 mW

C. Wang,…M. Loncar, Nature Communications, 10, 1, 2019

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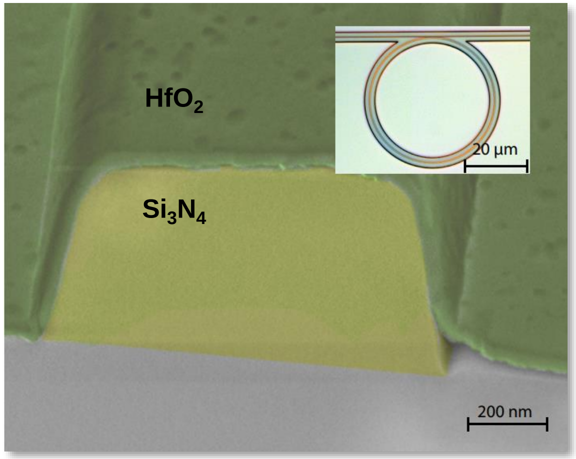
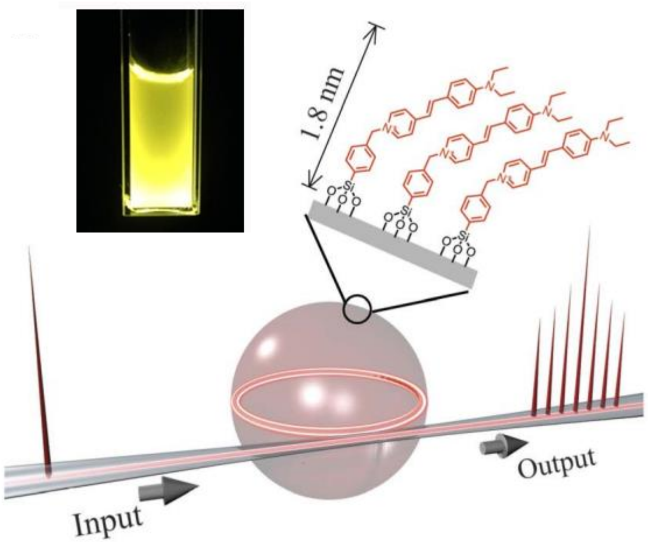
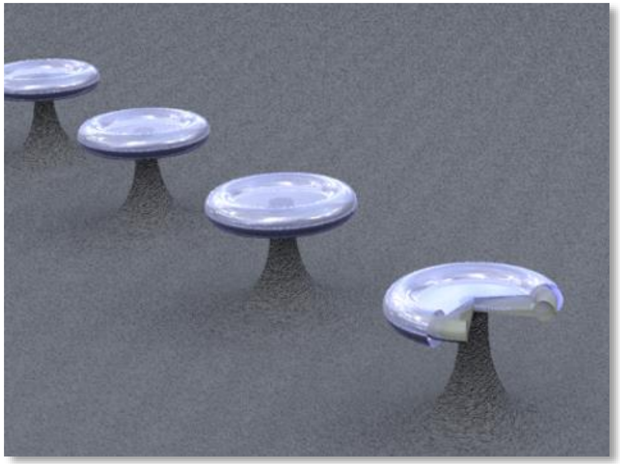
Unconventional, multi-material systems?

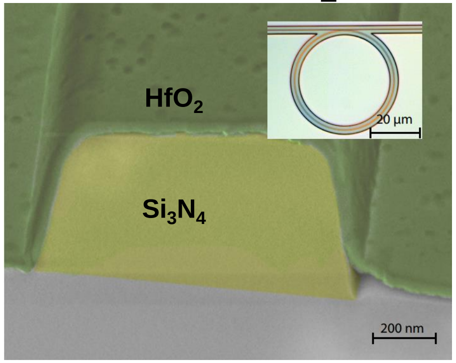






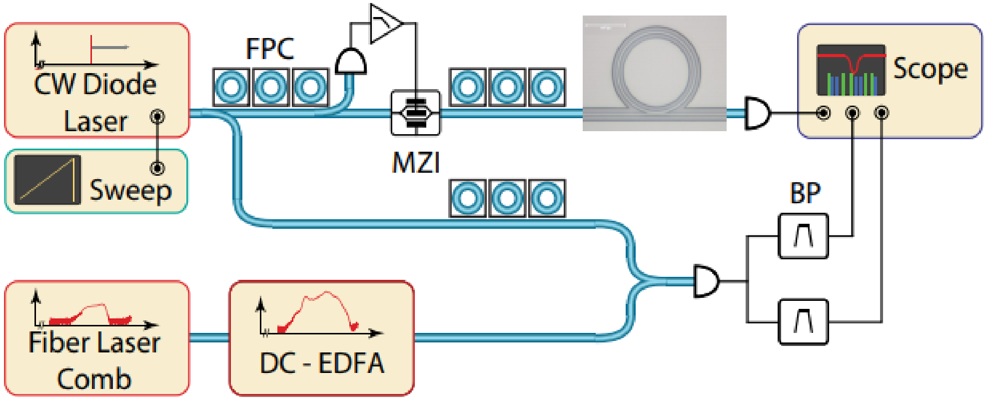
Dispersion engineering via ALD

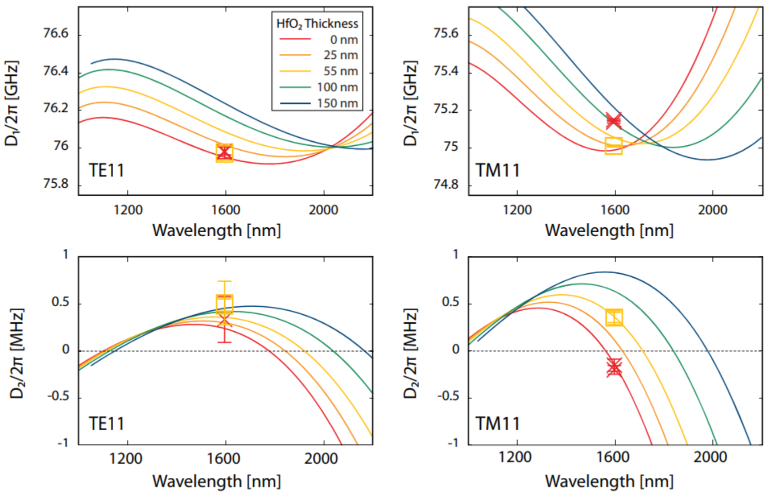
Addition of HfO_2 Layer



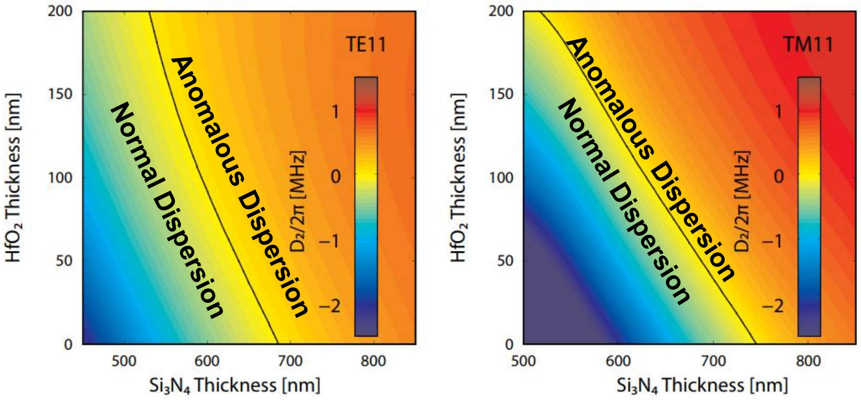
Silicon Nitride Microring
Q ~ 6×10^5

Dispersion Measurement





Significant cavity dispersion tunability

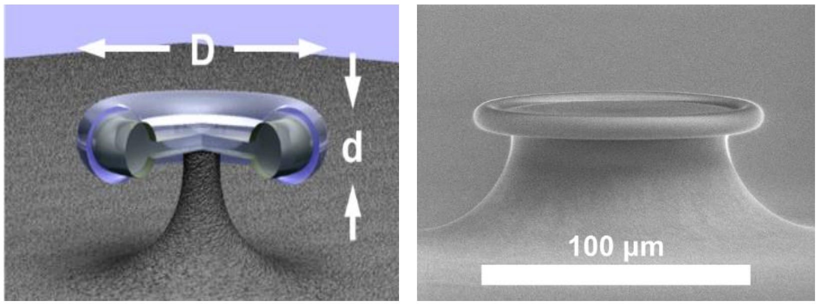


Traversing Regions of Dispersion

J. Riemensberger et al., Optics Express, 20, 25, 2015

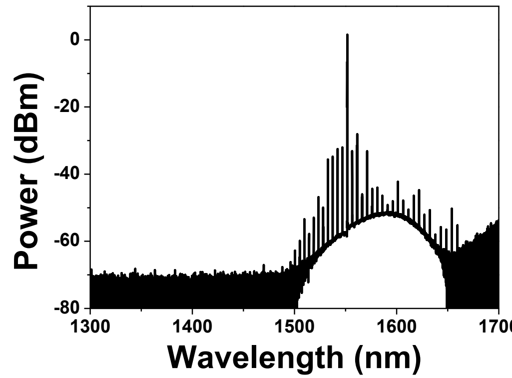
Zr-doped SiO_2 cavities

SiO_2 cavity with 400nm film



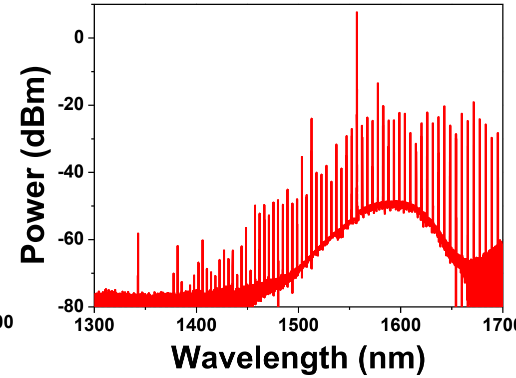
Q = ~1 x 10^7

0 Mol%, 5.24 mW

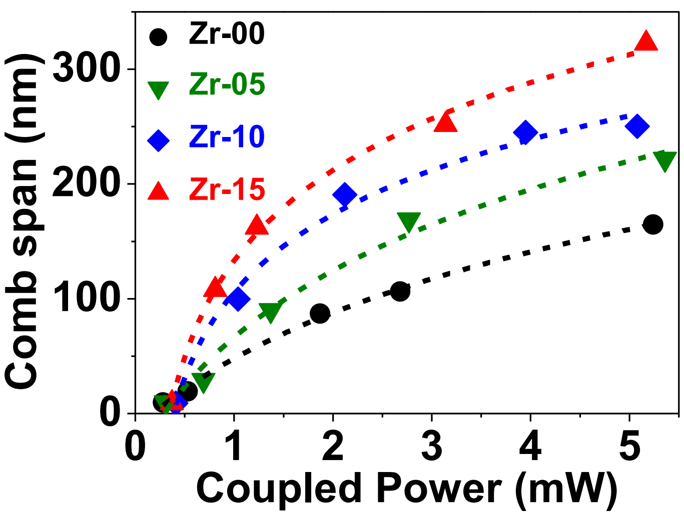


Span: 164 nm

15 Mol%, 5.17 mW



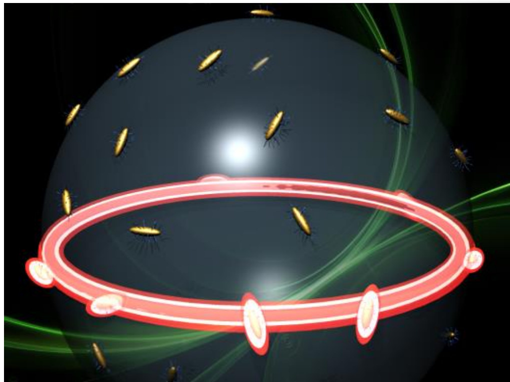
Span: 322 nm

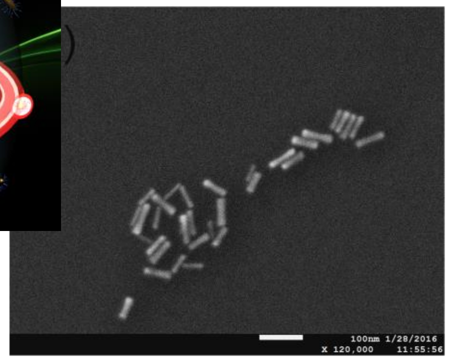


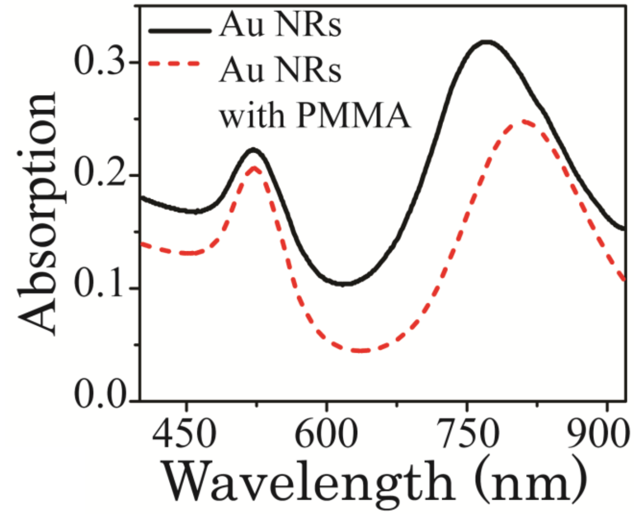
P_{th}=0.367mW

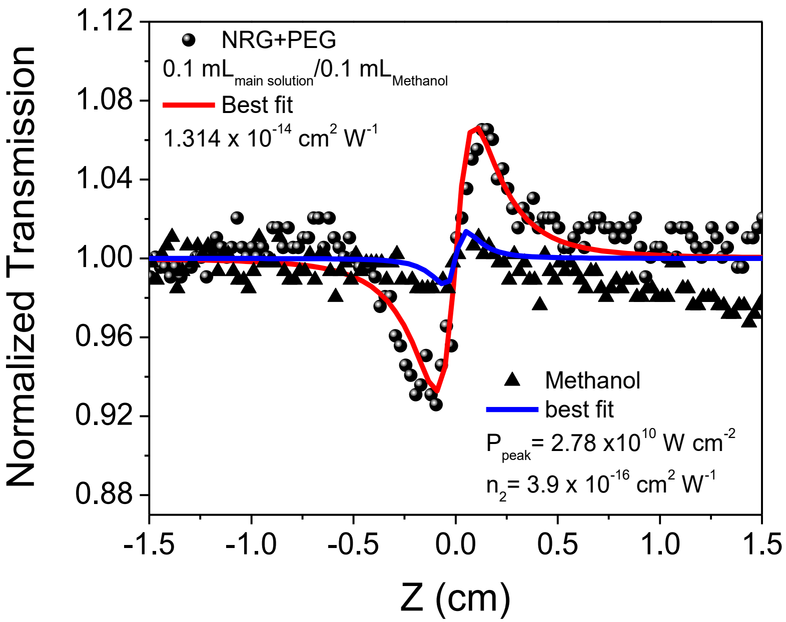
Span (5mW)=1378- ~1700 (322nm)

Plasmonic-photonic combs









Z-scan measurements confirm that the n_2 values of GNR-PEG nanoparticle ($1.3x10^{-18}m^2/W$) are ~100 times larger than silica ($2x20^{-20}m^2/W$)

	Kerr coefficient n_2 ($x10^{-20}m^2/W$)
• Silica	2.2
• Si_3N_4	25
• CaF_2	1.9
• Diamond	8.2

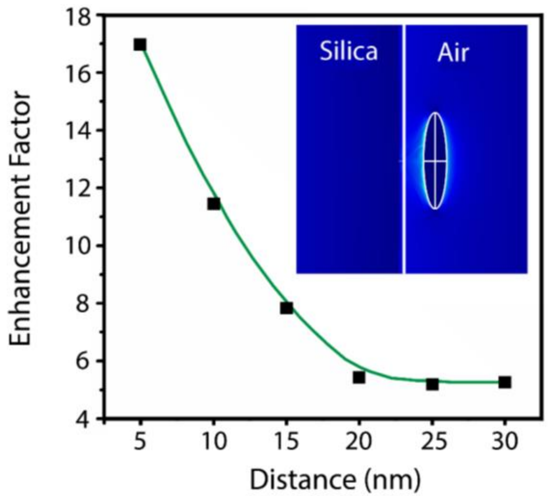
R. Castro-Beltran, … A. M. Armani, ACS Photonics, 4 (11) 2828 (2017).
C. Shi, S. Soltani, A. M. Armani, Nano Letters, 13 (12), 5827 (2013).

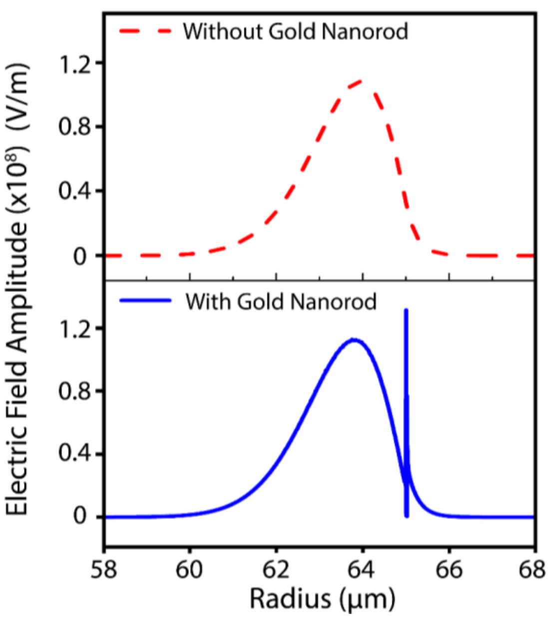
FEM modeling of enhancement

FEM predicts enhancement at short distances

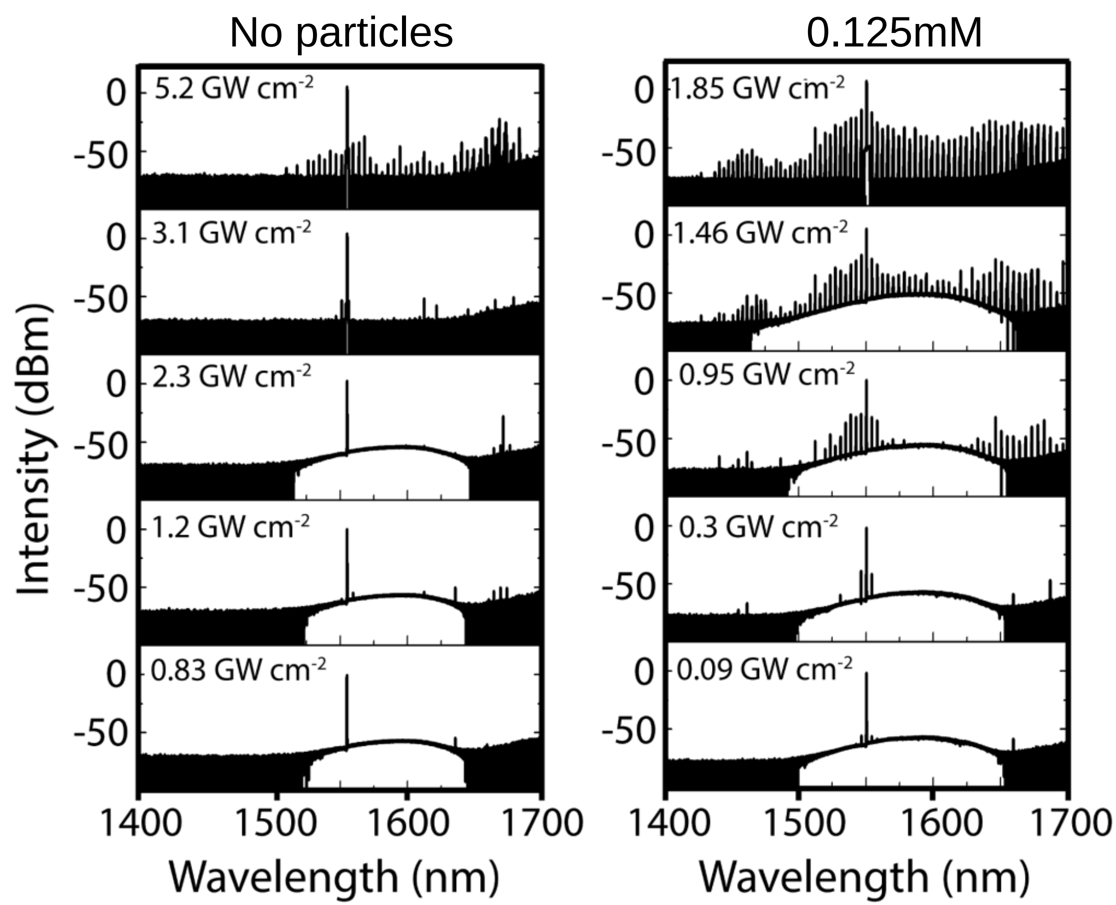
Q>10^7

P_{th}<1mW





Improvement seen in fabricated devices



R. Castro-Beltran, … A. M. Armani, ACS Photonics, **4** (11) 2828 (2017).

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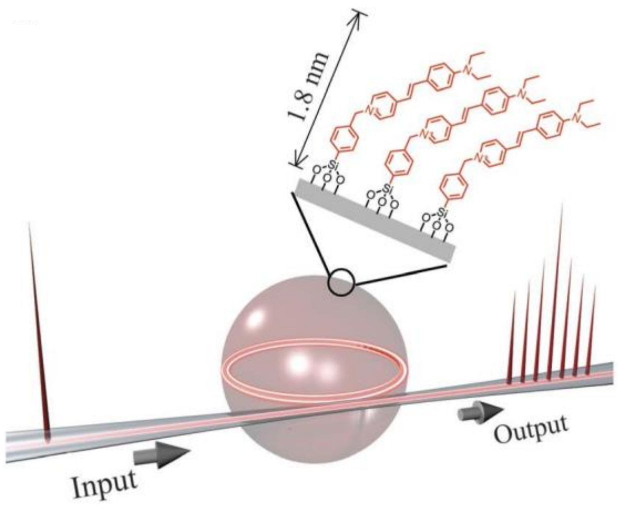
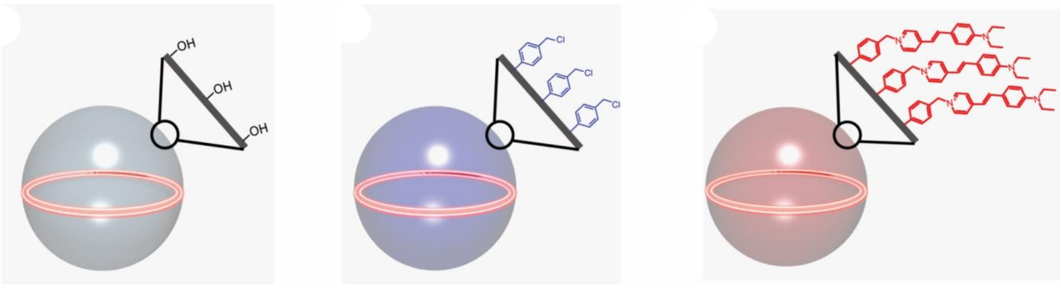
Small organic molecule monolayers

Enables access to higher $\chi^{(3)}$:

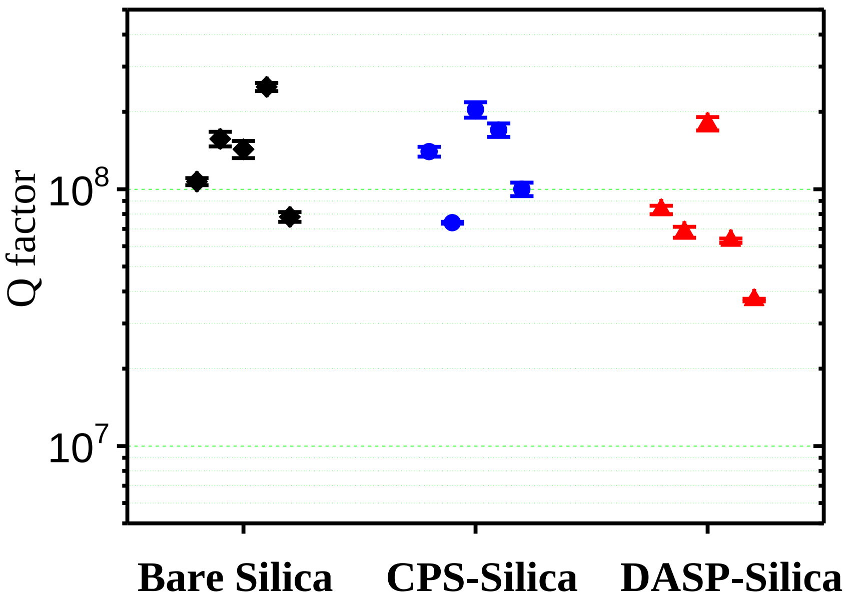
- $n_{2,\ silica} = 2.2 \times 10^{-20} m^2/W$
- $n_{2,\ DASP} = 2.6 x 10^{-15} m^2/W$



138μm diameter silica sphere



Initial silica device | CPS-silica device | DASP-silica device



CPS: chloromethylphenyl silane
DASP: 4-[4-diethylamino(styryl)]pyridinium

X. Shen,… A. Armani, Sci. Adv., 4, 2018

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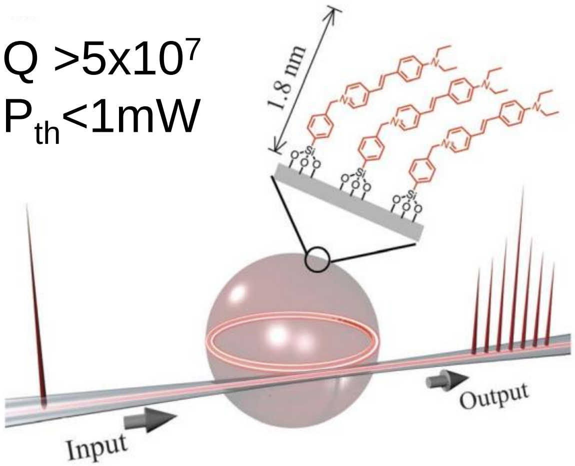
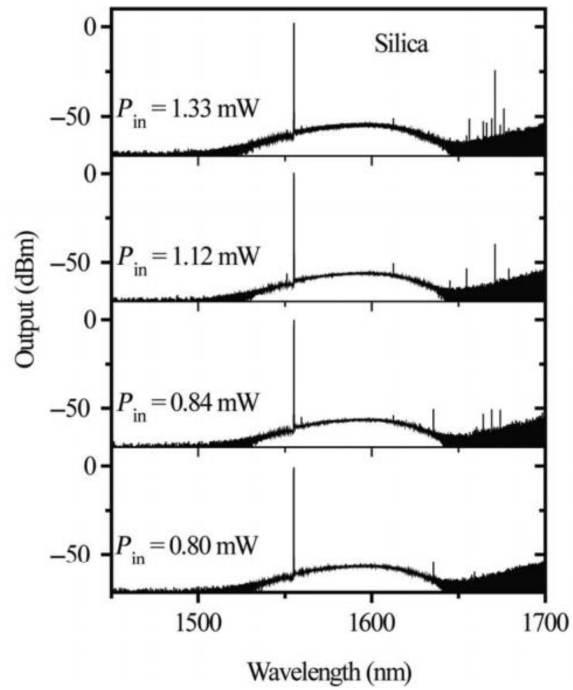
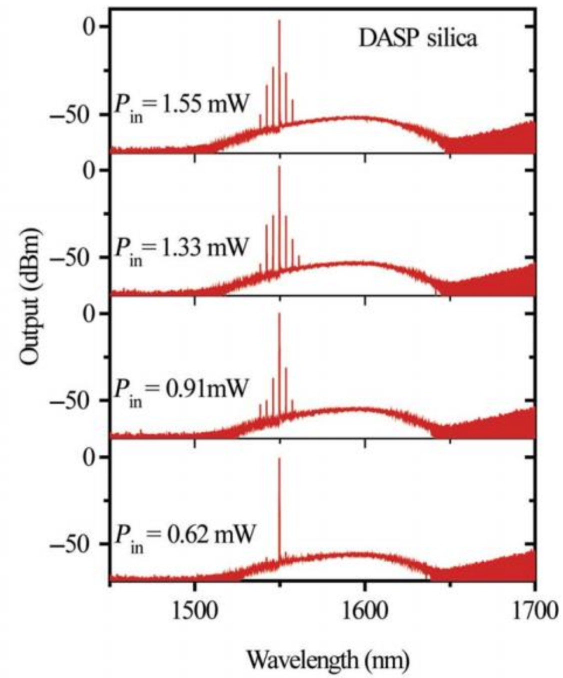
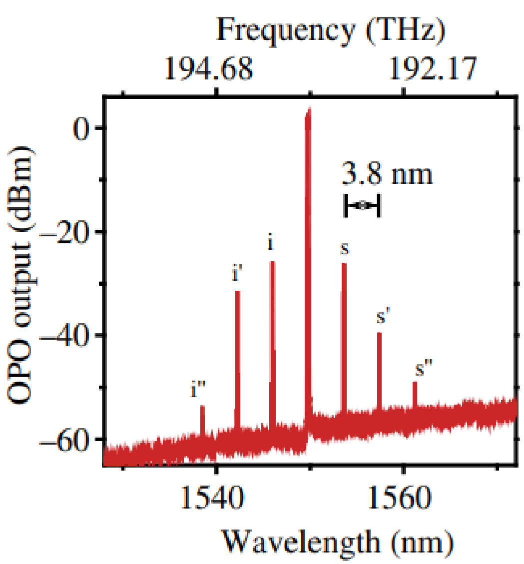
Small organic molecule monolayers

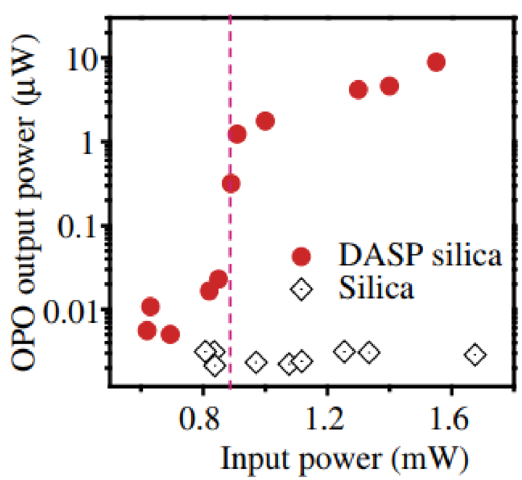
Q >$5x10^7$
P_{th}<1mW







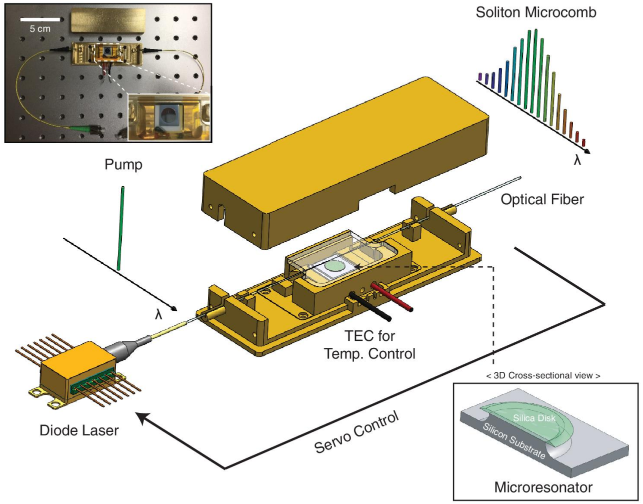


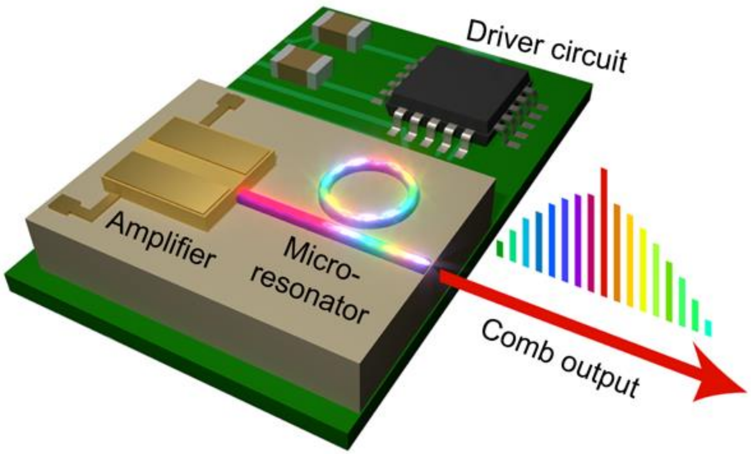


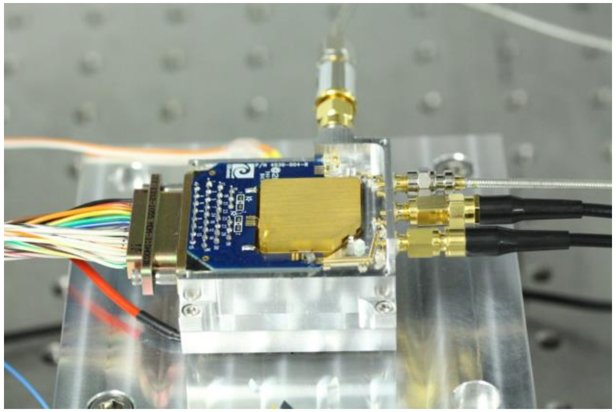
CPS: chloromethylphenyl silane
DASP: 4-[4-diethylamino(styryl)]pyridinium

X. Shen,… A. Armani, Sci. Adv., 4, 2018

Portable combs?







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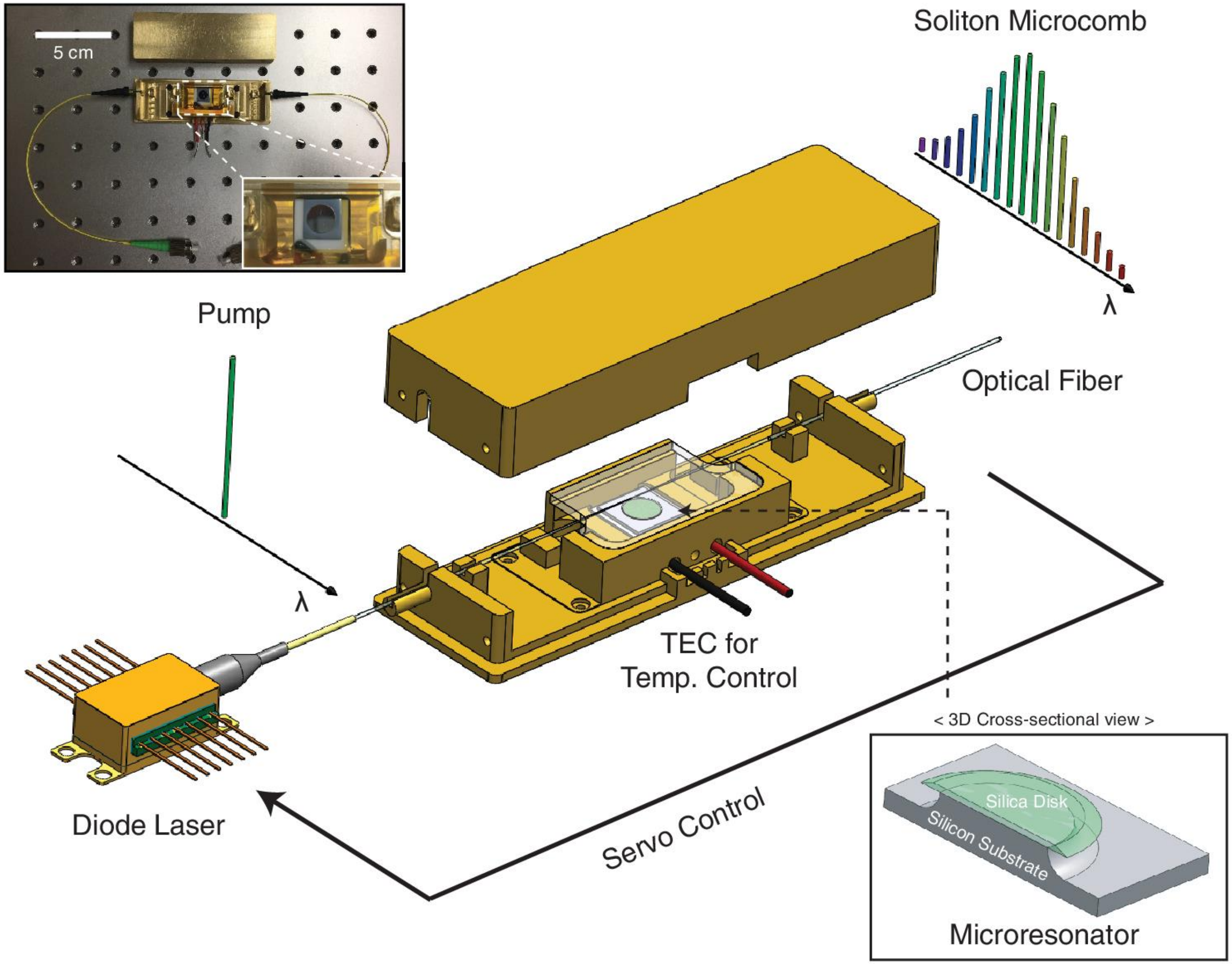
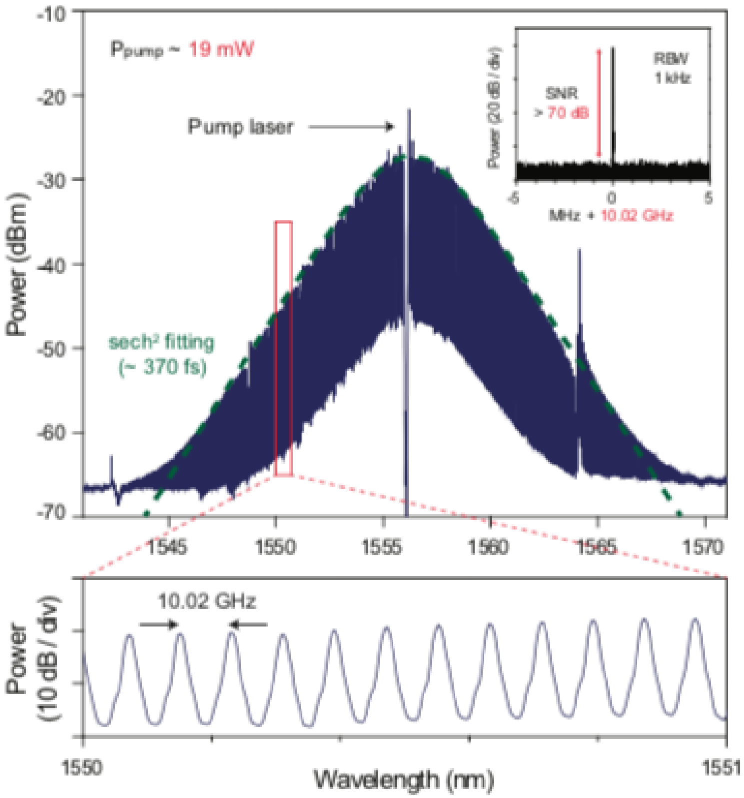
Microcomb Module

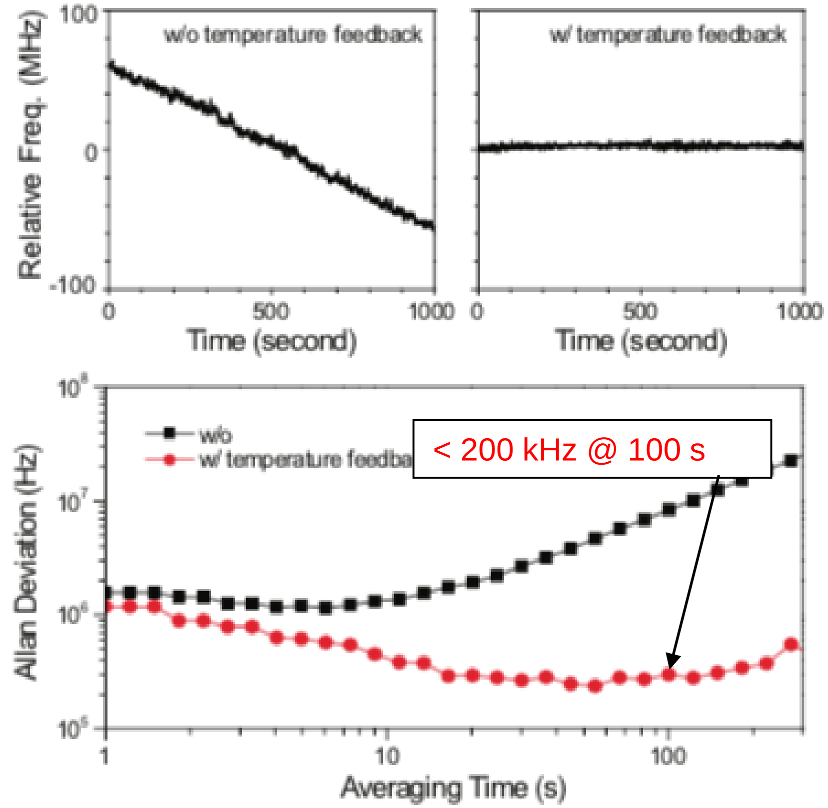


MG Suh, et al., *Optics Letters* (2019).

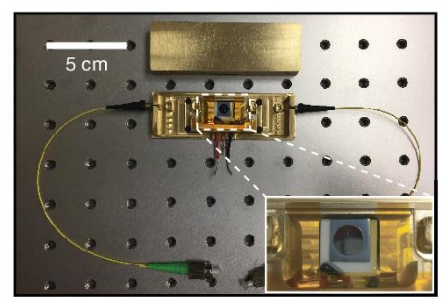
Direct Pumping of 10 GHz Soliton Microcomb

Caltech





- 10 GHz soliton microcomb module
- Directly-pumped by a low power (< 20 mW) diode laser.
- Absolute frequency instability of < 200 kHz @ 100 second averaging

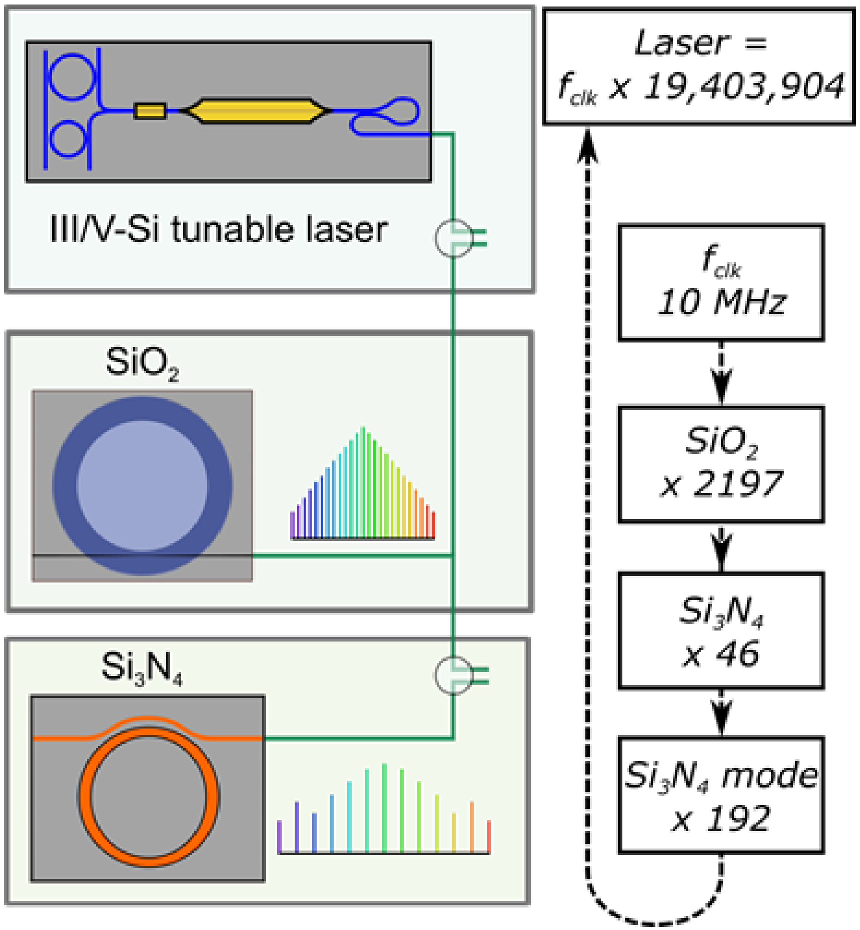


MG Suh, et al., *Optics Letters* (2019).

USC Viterbi
School of Engineering

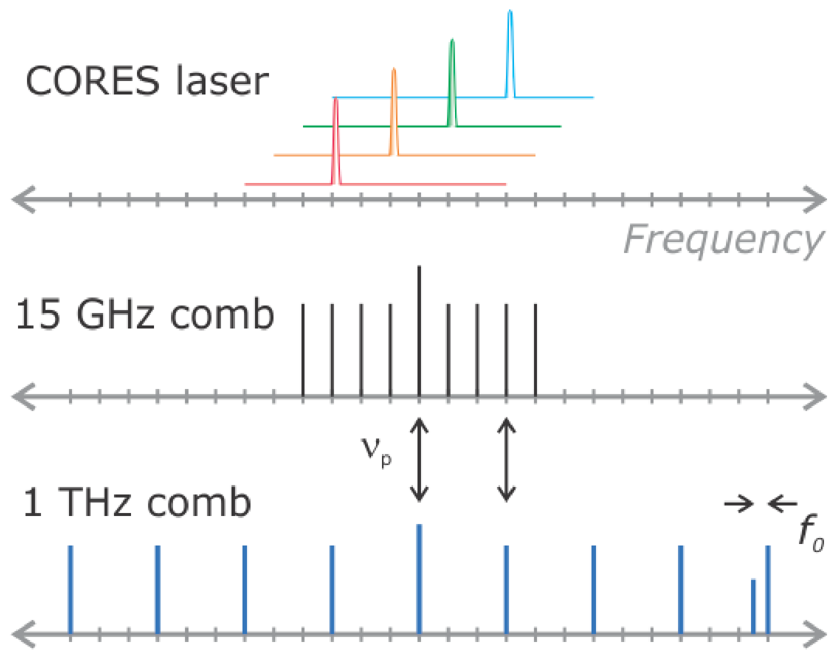
Microcomb optical frequency synthesizer

UCSB / NIST / Caltech / EPFL / UVa / Aurrion
DARPA DODOS



Three ingredients

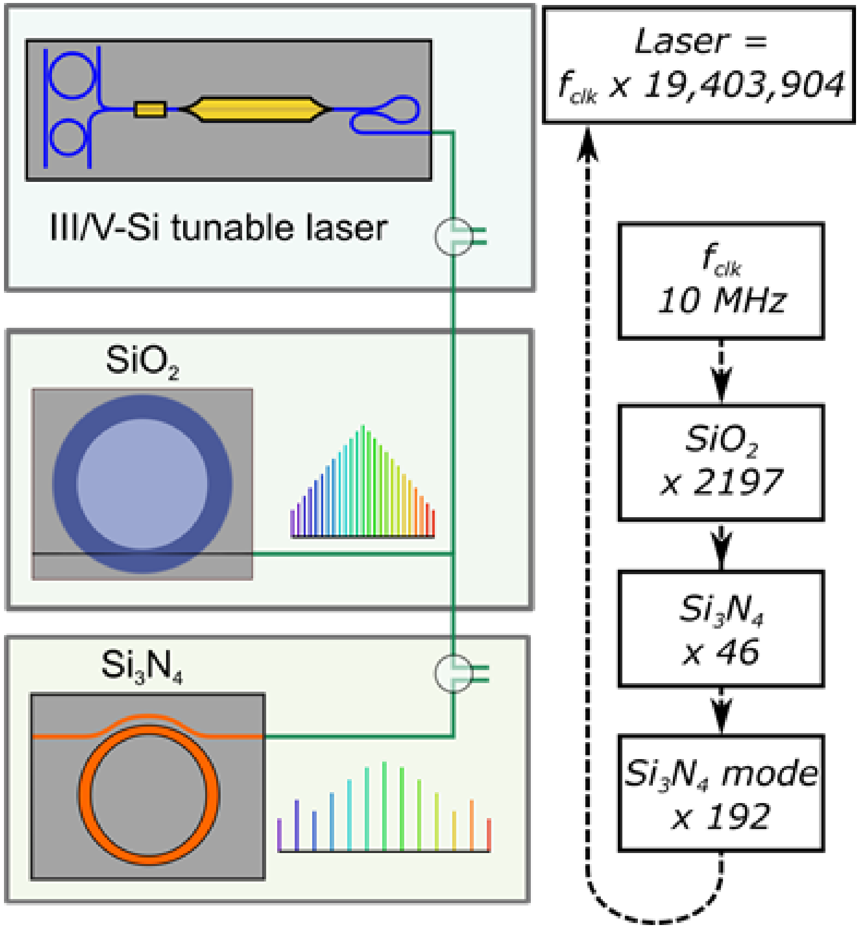
1. Self-referenced SiN THz comb
2. 15 GHz SiO_2 comb
3. Tunable CW laser in C-band



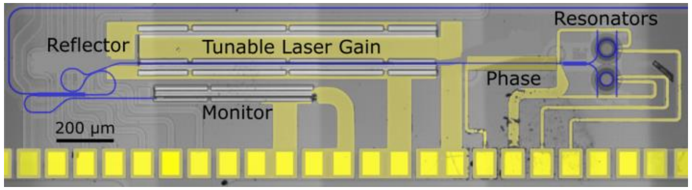
Daryl Spencer, Tara Drake, Travis Briles, Jordan Stone, et al *Nature* (2018)

Microcomb optical frequency synthesizer

UCSB / NIST / Caltech / EPFL / UVa / Aurrion
DARPA DODOS

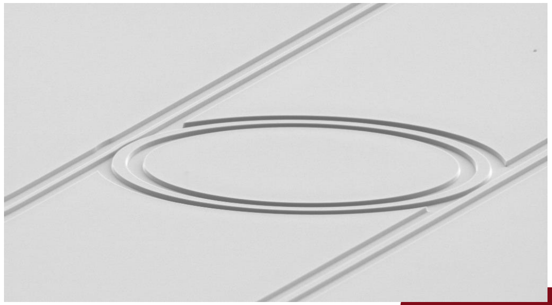


Chip tunable laser (UCSB, Aurrion)



15 GHz SiO_2 disks (Caltech)

1 THz SiN (NIST-G)

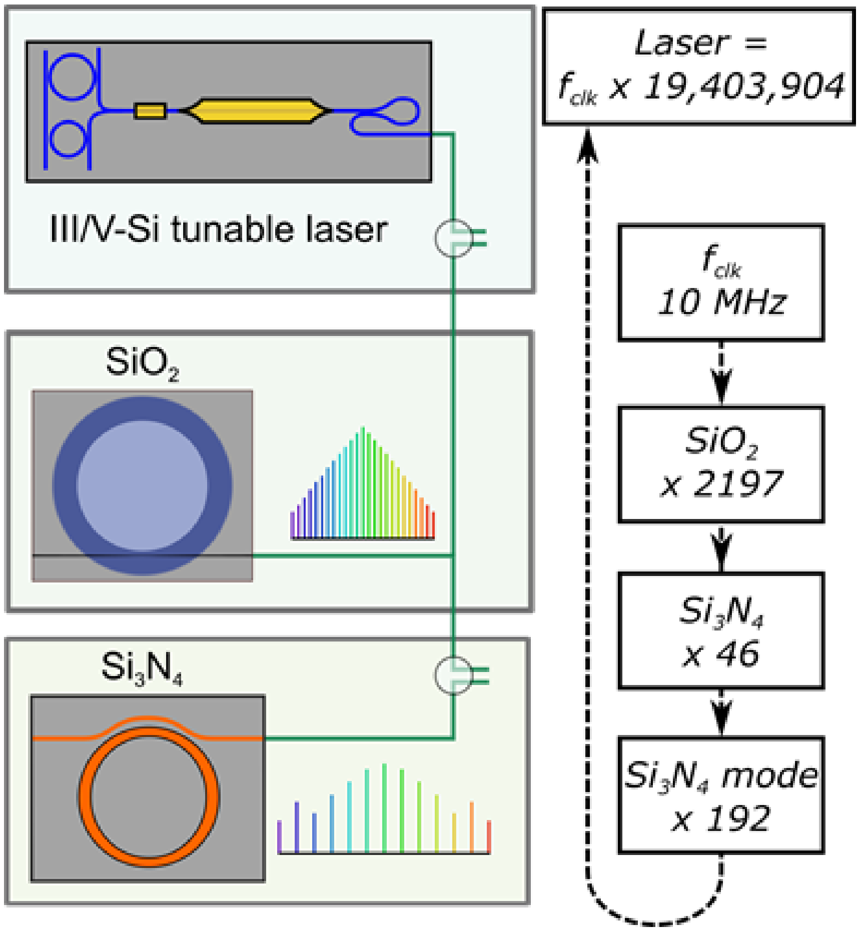


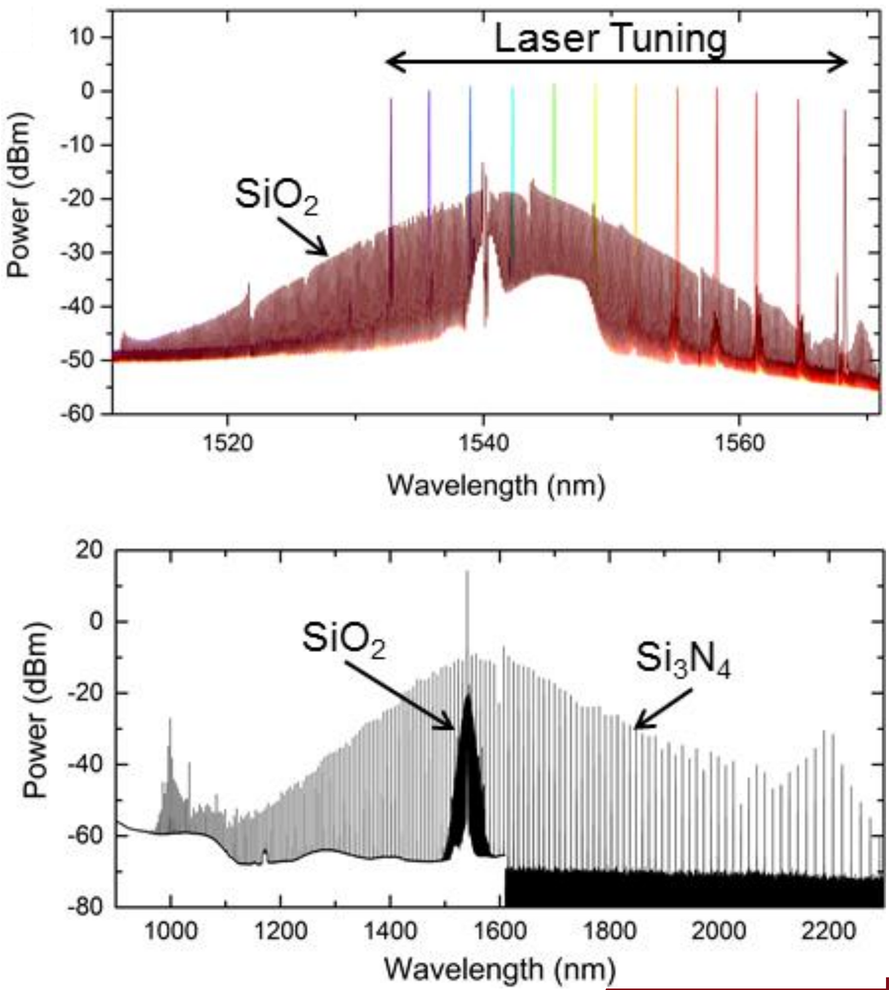
Daryl Spencer, Tara Drake, Travis Briles, Jordan Stone, et al *Nature* (2018)

USC Viterbi School of Engineering

Synthesizer frequency control

UCSB / NIST / Caltech / EPFL / UVa / Aurrion
DARPA DODOS





Daryl Spencer, Tara Drake, Travis Briles, Jordan Stone, et al *Nature* (2018)

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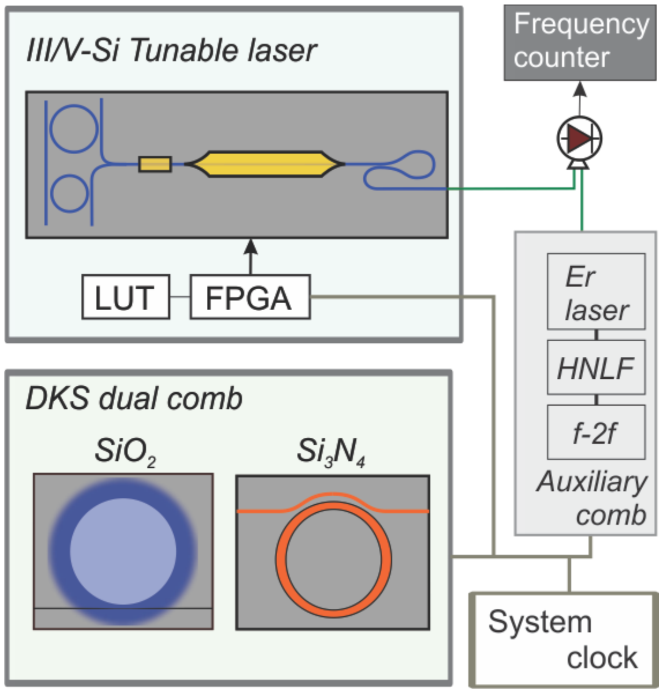
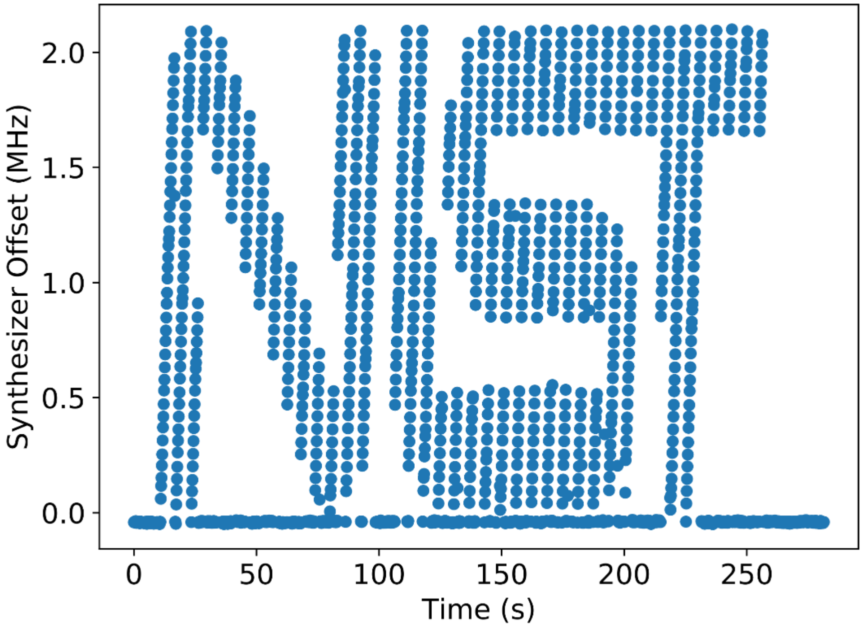
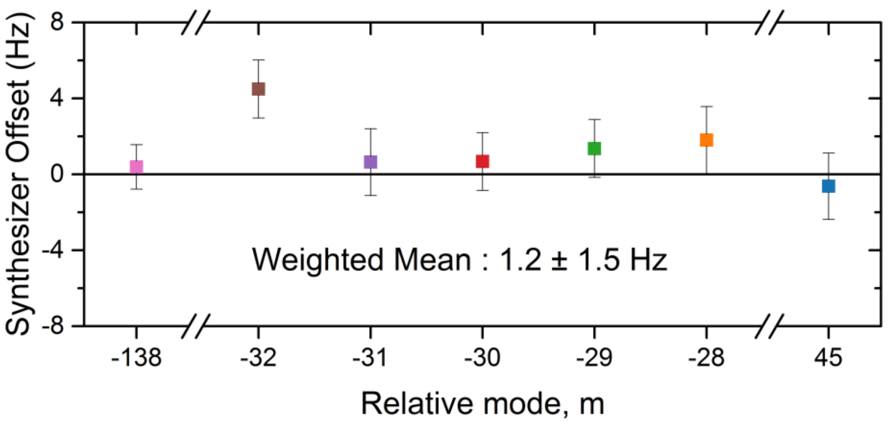
Synthesis across the C-band

- Rapid synthesis of arbitrary frequencies in C-band
- Accurate at the 1 Hz level



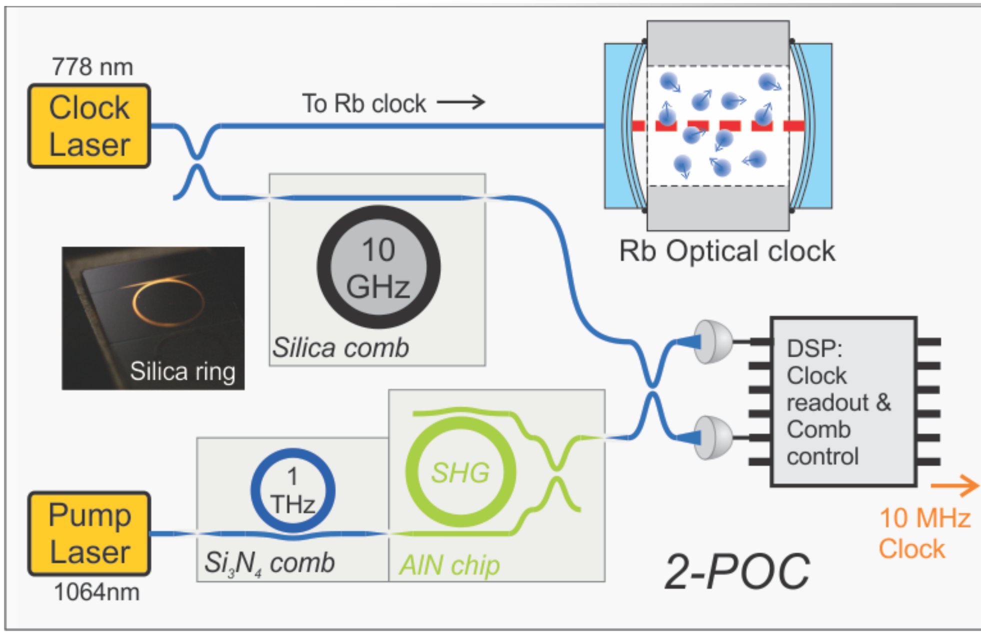




UCSB / NIST / Caltech / EPFL / UVa / Aurrion
DARPA DODOS

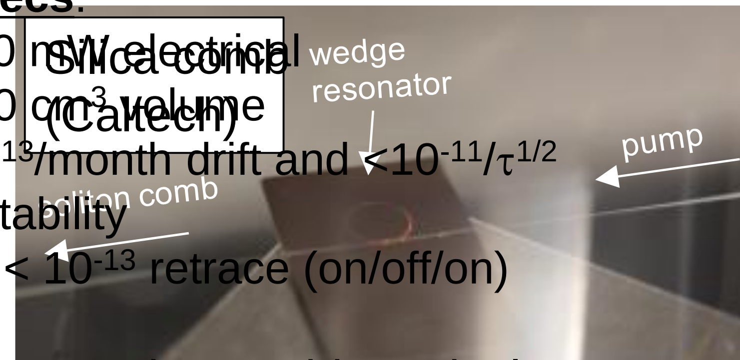
Daryl Spencer, Tara Drake, Travis Briles, Jordan Stone, et al *Nature* (2018)

A microcomb optical atomic clock



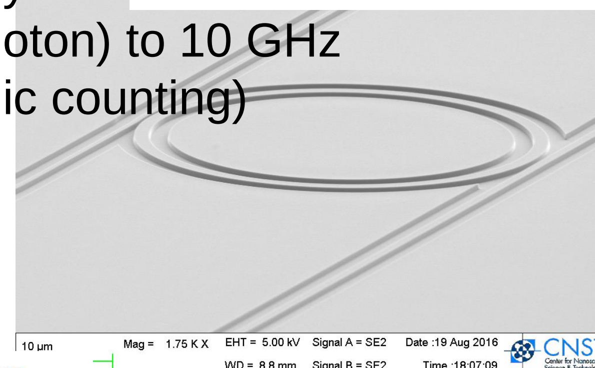
Specs:
250 mW electrical
<50 cm^3 volume
10^{-13}/month drift and $<10^{-11}/\tau^{1/2}$ instability
$\Delta y < 10^{-13}$ retrace (on/off/on)

Silica comb (Caltech)

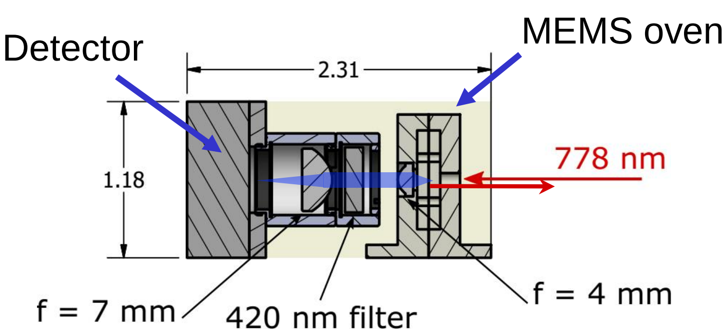


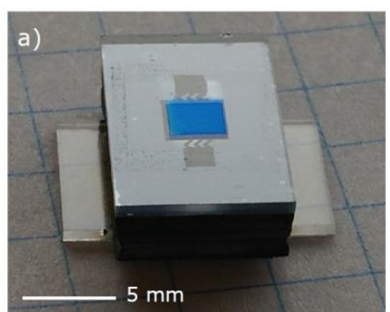
Microcombs provide optical frequency division from 385 THz (Rb 2-photon) to 10 GHz (electronic counting)

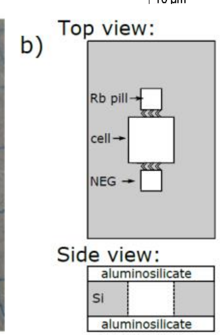
SiN combs (NIST)



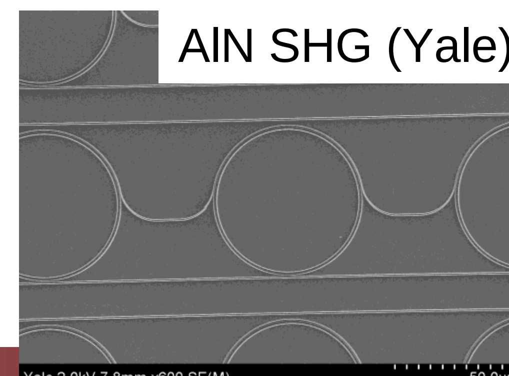
Rb optical clock (NIST-B Atomic Devices)





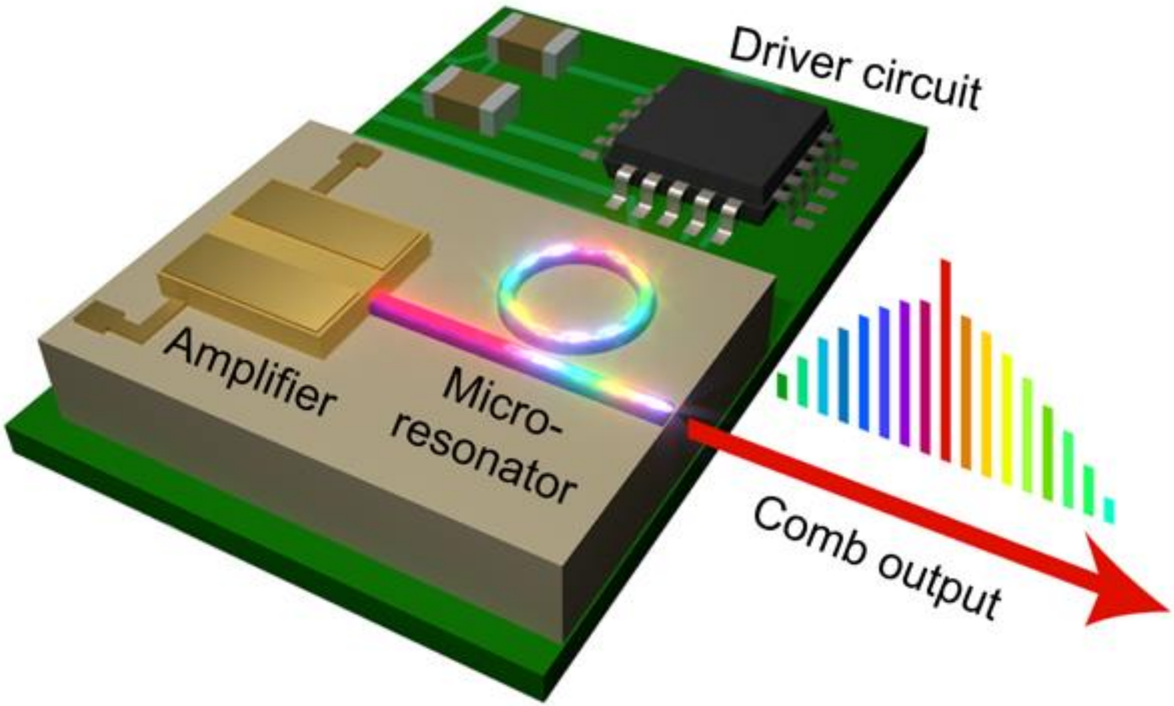


AlN SHG (Yale)

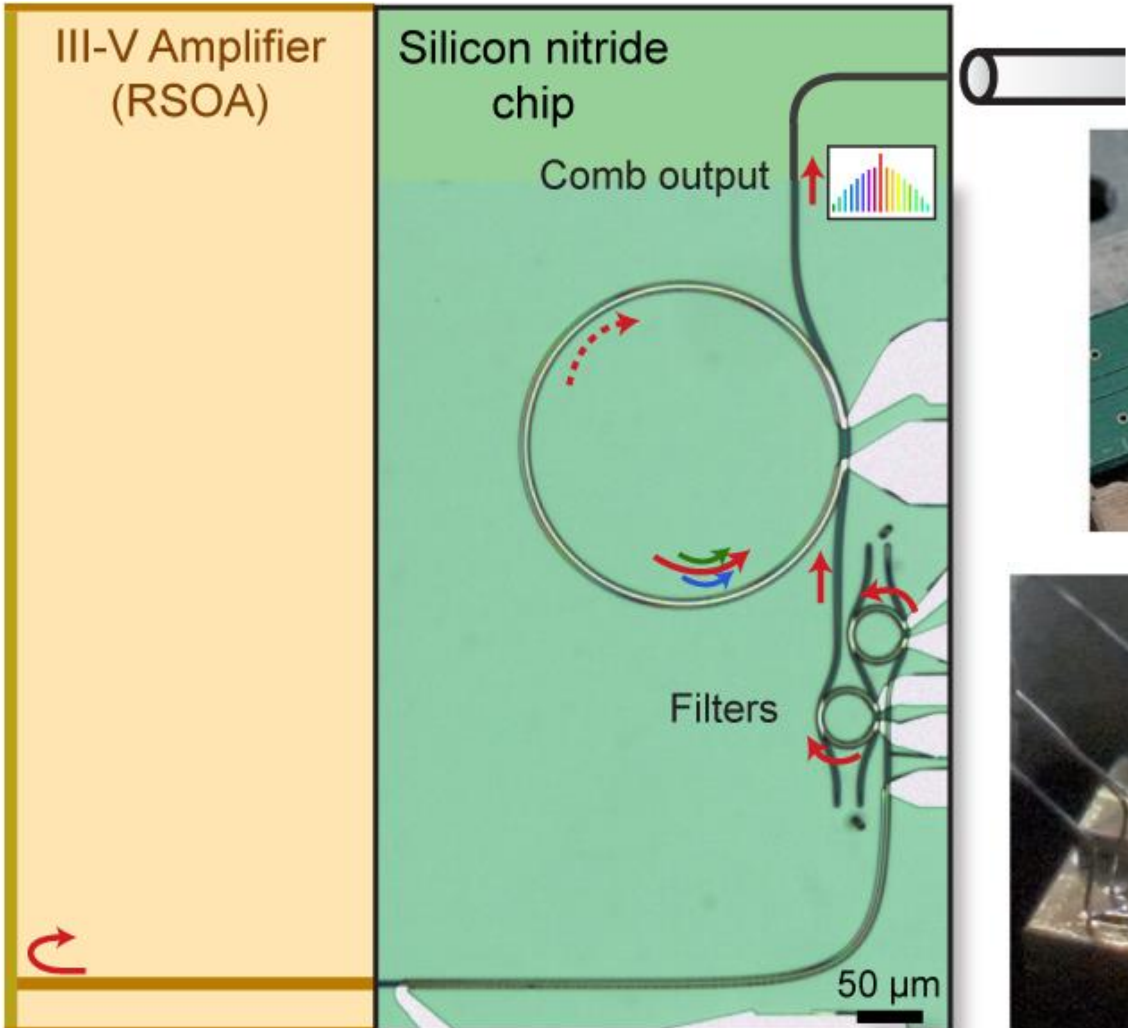


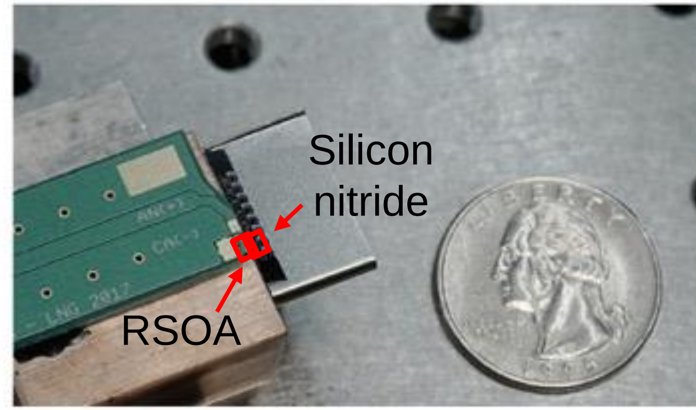
Draper / NIST / Caltech / Yale / Stanford / Ligentec

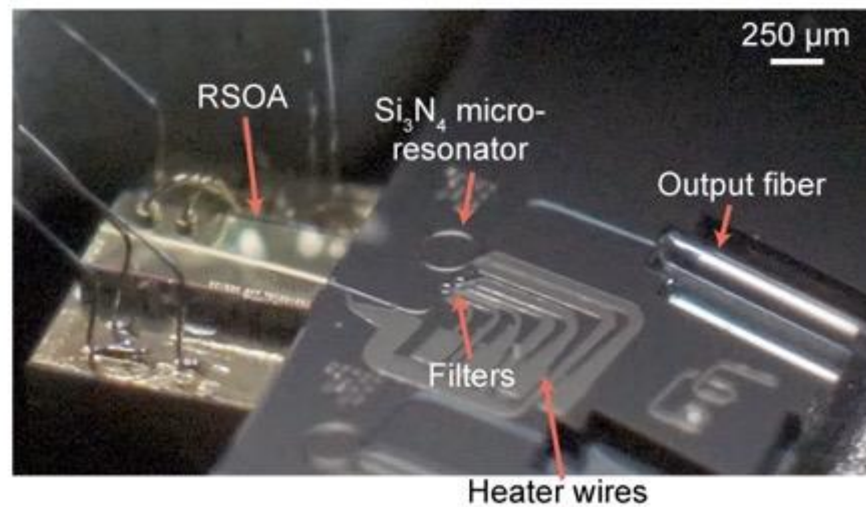
Integrated Comb Platform



Integrated Comb Platform



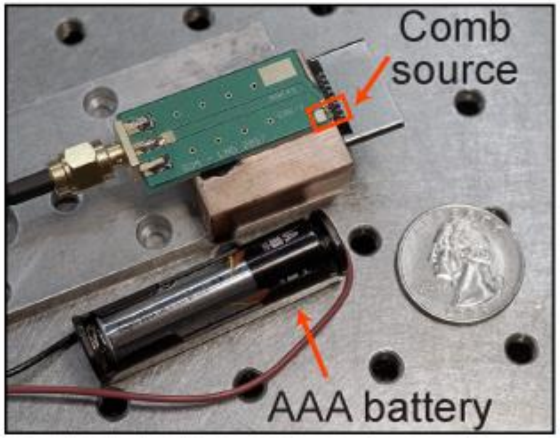


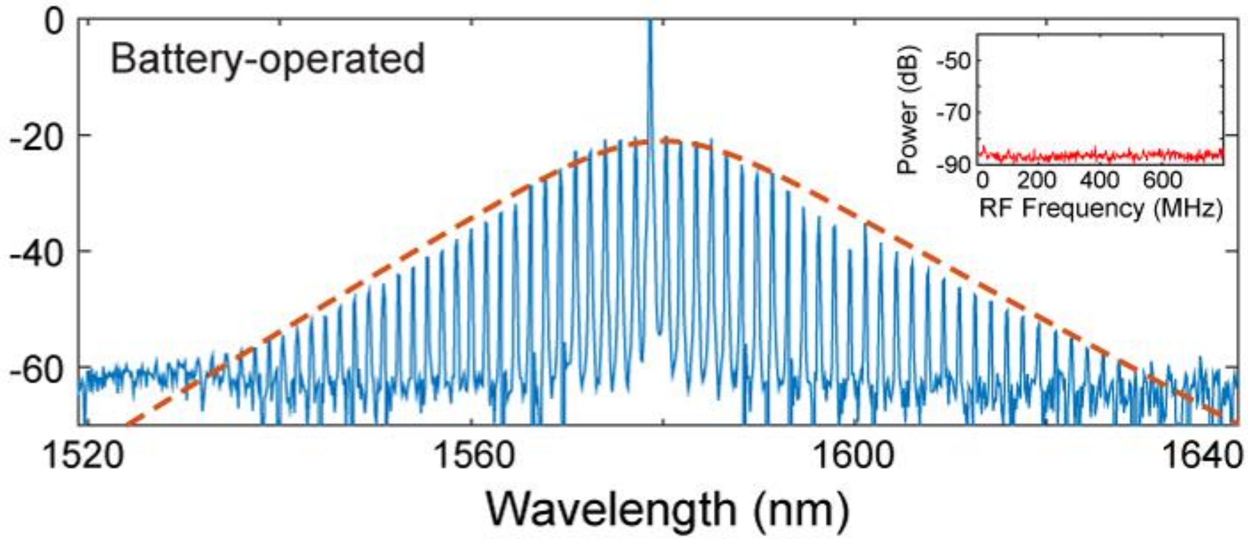


Stern, Gaeta, Lipson et al, Nature (2018); Stern, Lipson, Opt. Lett., 2017.

Battery Powered Comb

Columbia University in the City of New York





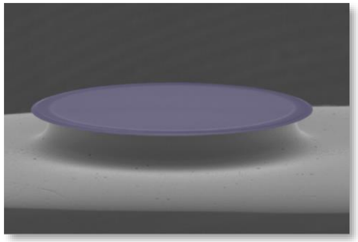
Optical pump power: 2.5 mW
Electrical power consumption: 130 mW

Optical pump power: 1.3 mW
Electrical power consumption: 98 mW

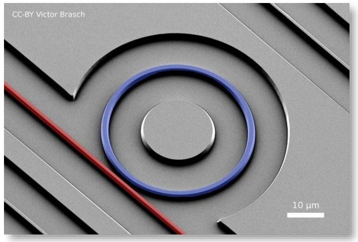
Stern, Gaeta, Lipson et al, Nature (2018); Stern, Lipson, Opt. Lett., 2017.

Conclusions

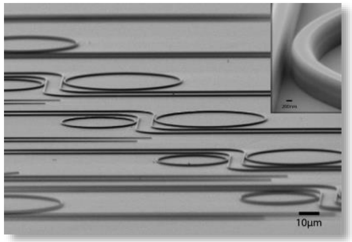
Fluorides



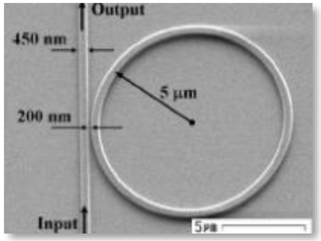
Oxides



Nitrides



Diamond



Silicon

Goals:

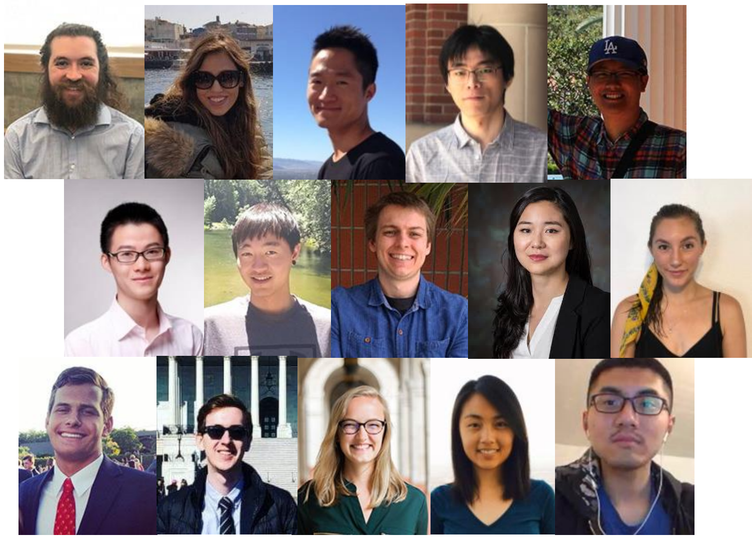
- High circulating intensity
- Precise mode spacing over large wavelength range
- Integrated, packaged system

Approaches:

- High Q, small V (high F)
- Large diameter
- Low (controllable) dispersion
- Designing for packaging

Acknowledgements

Post-docs/Graduate Students



Undergrad Students

Friends who shared slides

Scott Diddams (NIST)
Michal Lipson (Columbia)
Andrey Matsko (OEWaves)
Kartik Srinivasan (NIST)
Myoung-Gyun Suh (Caltech)

More info

http://armani.usc.edu

@ArmaniLab

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Related presentations

Wednesday:

- Optically Generated 10-GHz Signal with 10 Microradian Residual Phase Instability (**SW4G.1**)

Thursday:

- Near-Visible Microresonator-Based Soliton Combs (**STh3J.1**)
- Dual-comb imaging using soliton microcombs (**STh4J.3**)
- Measurement of the Earth's Rotation Using a Chip-Based Brillouin Laser Gyroscope (**JTh5A.8**)

Friday:

- Broadband High-Resolution Scanning of Soliton Micro-Combs (**SF3H.6**)
- 30 GHz Supercontinuum Generation for Astronomy with Efficient SiN Waveguides (**FF2D.6**)