A Revolution in High-Q Integrated Photonics

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Optica Webinar
Technical Group: Optical Fabrication and Testing
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Outline

- Background on high-Q whispering gallery resonators

- Early exploration of high-Q science:
  - Parametric oscillators
  - Harmonic generation
  - Cavity optomechanics
  - Cavity QED
  - Bio Sensing

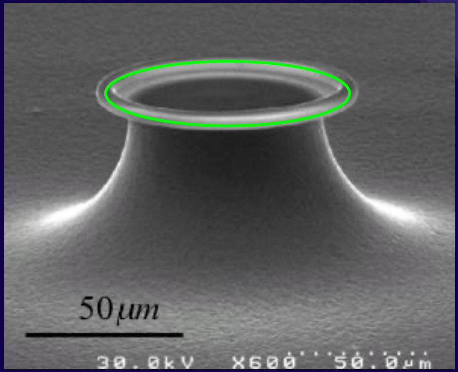
- Recent Progress (Technology and Integration):
  - Optical Gyroscopes
  - Miniature frequency combs
  - High Coherence Sources

- Outlook

Early High-Q Microresonators

- Earliest high-Q resonators were liquid droplets or solid droplets (microspheres). Surface tension smoothed resonator finish to reduce scattering.
- Microtoroids brought this idea to silicon wafers.
- Silica, and Mg/CaF_2 resonators lowered material loss.
- Q's from 100 million to 100 billion demonstrated.
- All devices lacked coupled waveguides. Required fiber tapers or prism in order to couple light to and from resonator.

Microtoroid Resonator

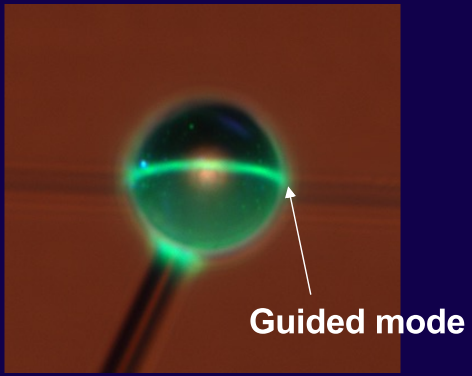


Armani, Kippenberg, Spillane, Vahala, *Nature*, (2003).

Liquid Microsphere Resonators

R. Chang, Yale (1985)
A. Campillo, NRL (1986)

Silica Microsphere Resonators



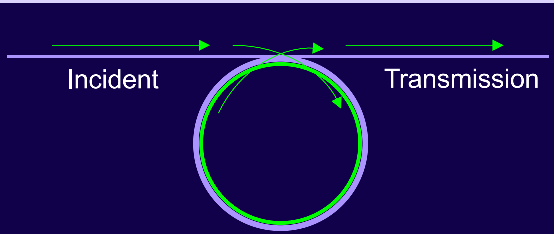
Braginsky, Goredetsky, Iltchenko (1989)

Crystalline Resonator

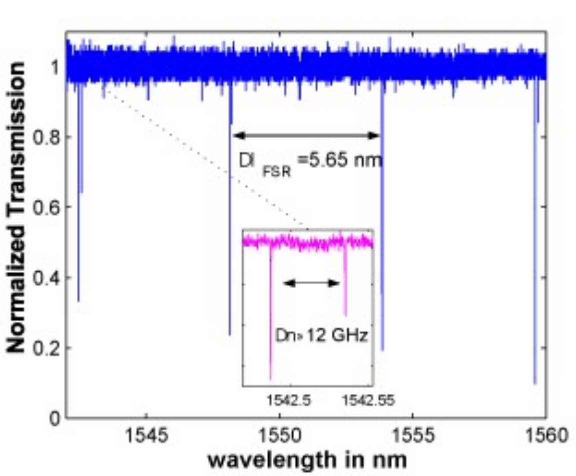
Savchenkov, Matsko, et al, Iltchenko,
Maleki, *Physical Review Letters*, (2004).

Appearance of resonances in transmission spectrum

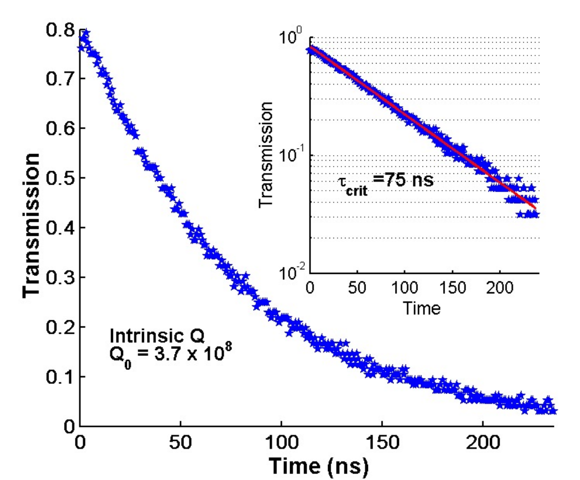
- High Q gives long energy storage time (photon lifetime)


Incident
Transmission

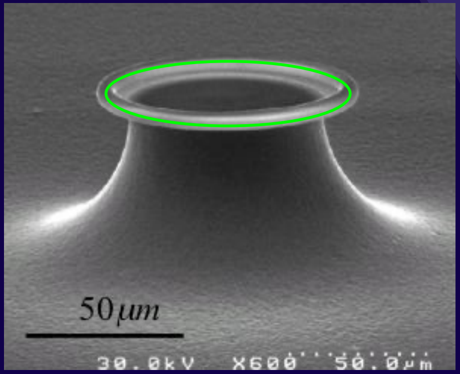
Transmission spectrum



Photon lifetime ring down



Microtoroid Resonator



Armani, Kippenberg, Spillane, Vahala, *Nature*, (2003).

Crystalline Resonator

Savchenkov, Matsko, et al, Iltchenko,
Maleki, *Physical Review Letters*, (2004).

Very large resonant intensity buildup

- High Q gives long energy storage time (photon lifetime)
- Small resonator size leads to large energy density
- Result is high circulating intensity
- **Nonlinear optical phenomena at milliWatt power levels**

$$I_{circulation} = \frac{c}{V}\int_{t}^{t+\tau} P_{input}\, dt' \approx \frac{\mathbf{Q}}{\mathbf{V}}\frac{c}{\omega}P_{input}$$

V = 500 μm^3 (50 μm dia. microtoroid)

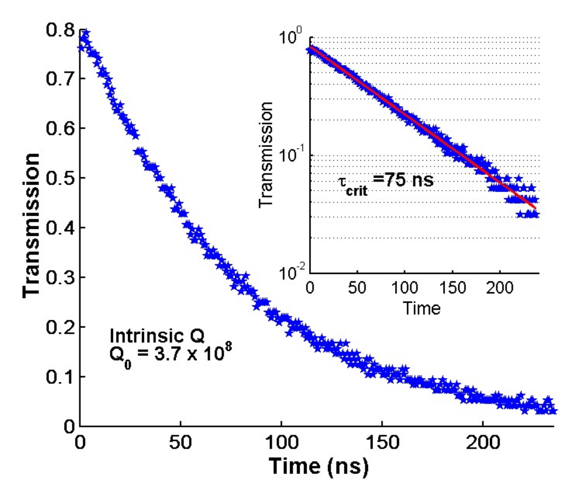
$Q = 10^8$

I_{circ} = 3 GWatts/cm^2

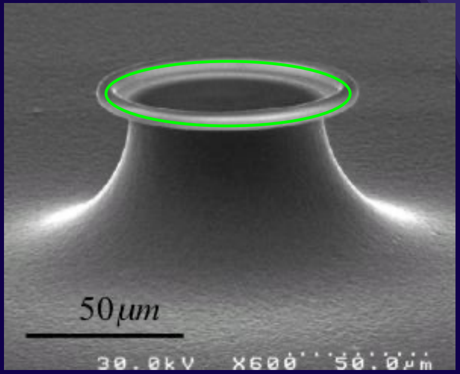
(1 mWatt input)

K. Vahala *Nature* (2003)

Photon lifetime ring down



Microtoroid Resonator



Armani, Kippenberg, Spillane, Vahala, *Nature*, (2003).

Crystalline Resonator

Savchenkov, Matsko, et al, Iltchenko, Maleki, *Physical Review Letters*, (2004).

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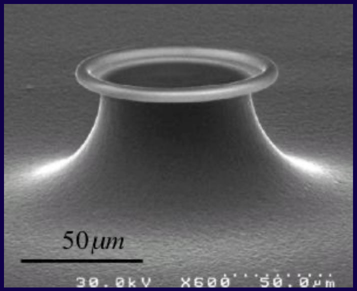
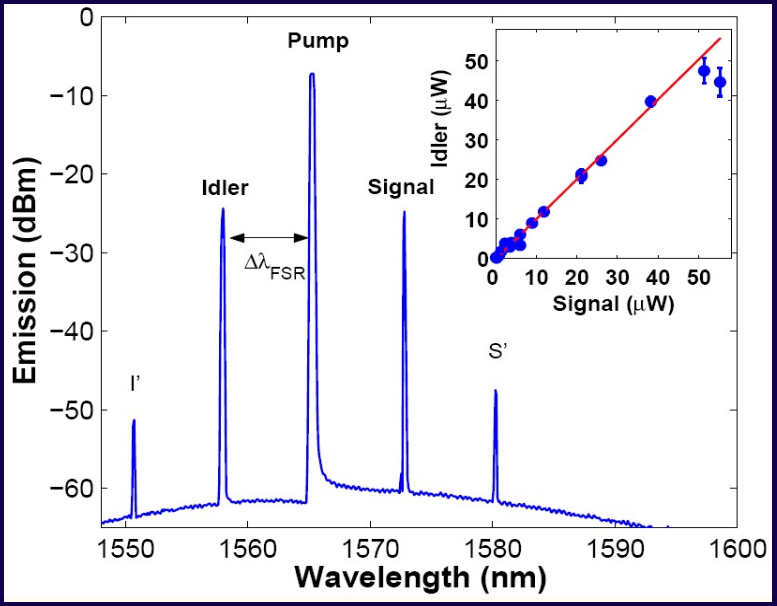
Important Example: Kerr Parametric Amplification & Regenerative Oscillation

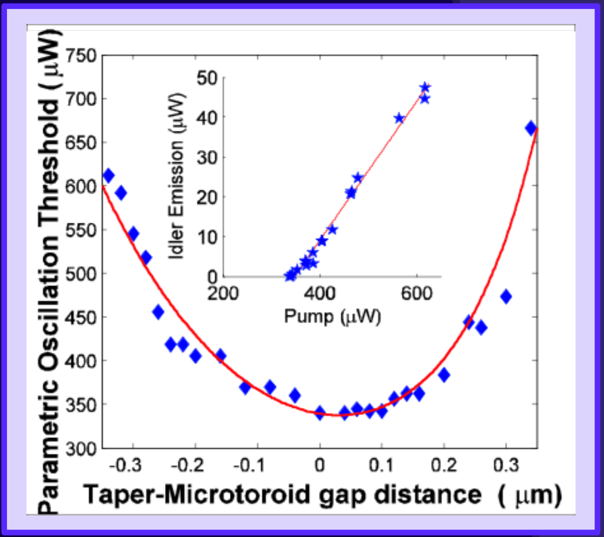
(Regeneration mechanism for microcombs)

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



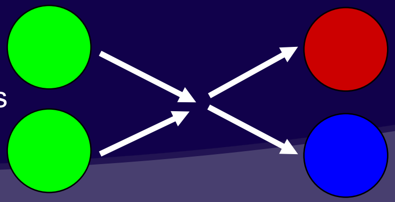
Kippenberg, Spillane, Vahala, *Physical Review Letters*, (2004).





$$P_{th} = \frac{\pi\, n\, \omega\, A}{4\, \eta\, n_2} \frac{1}{FSR\, Q^2}$$

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



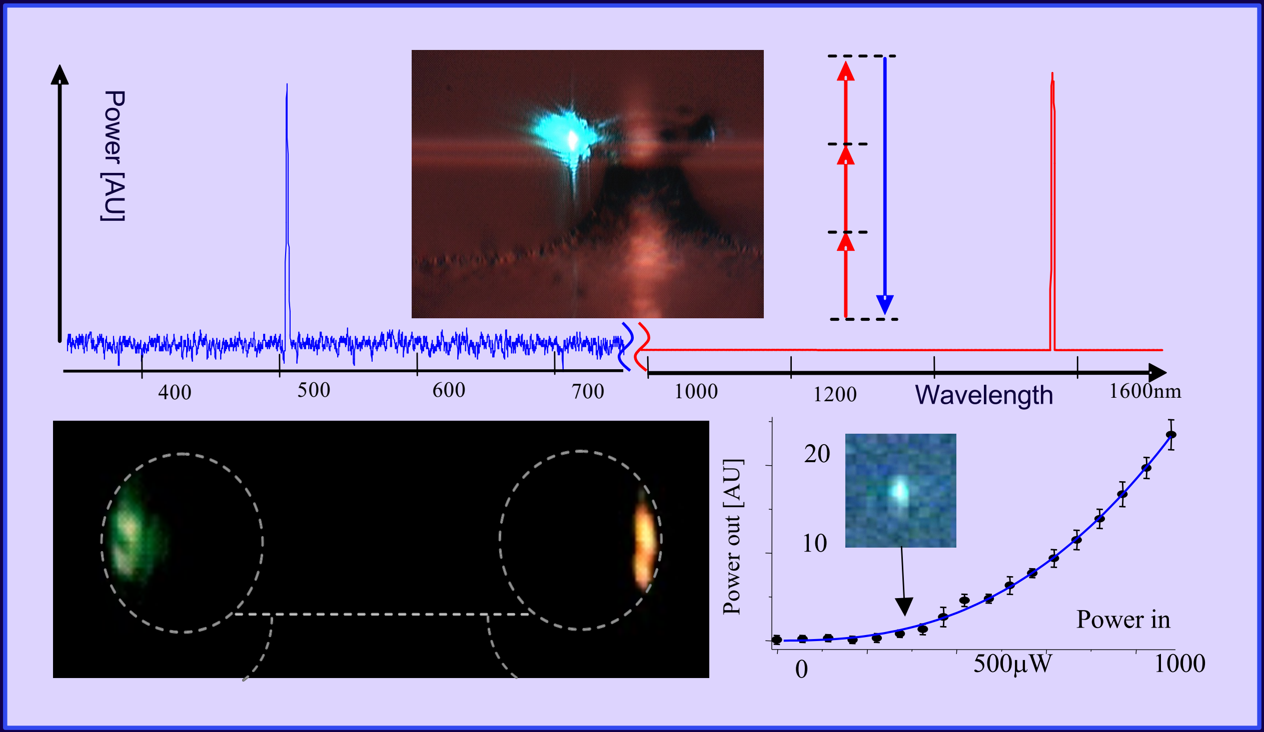
Pump photons

Signal

Idler

Tunable visible light generation

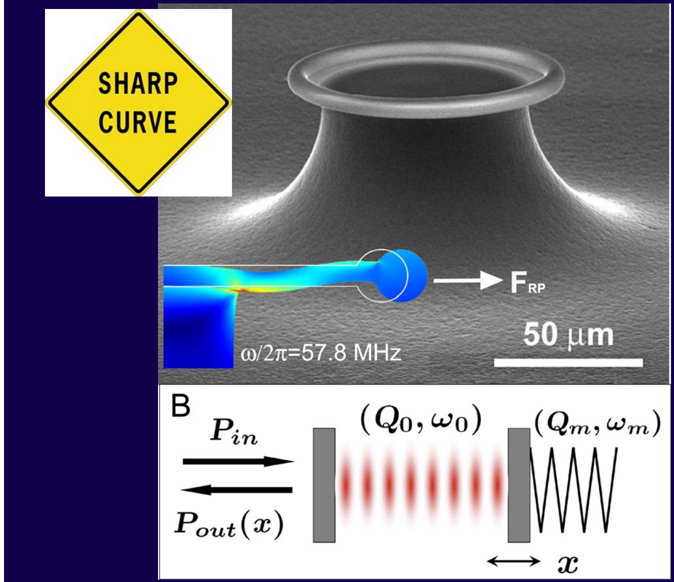
(Third harmonic generation)



Carmon, Vahala, Nature Physics (2007)

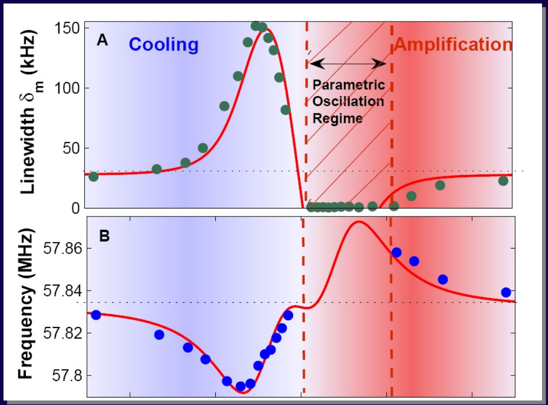
Cavity Optomechanics

Mechanical amplification and regenerative oscillation



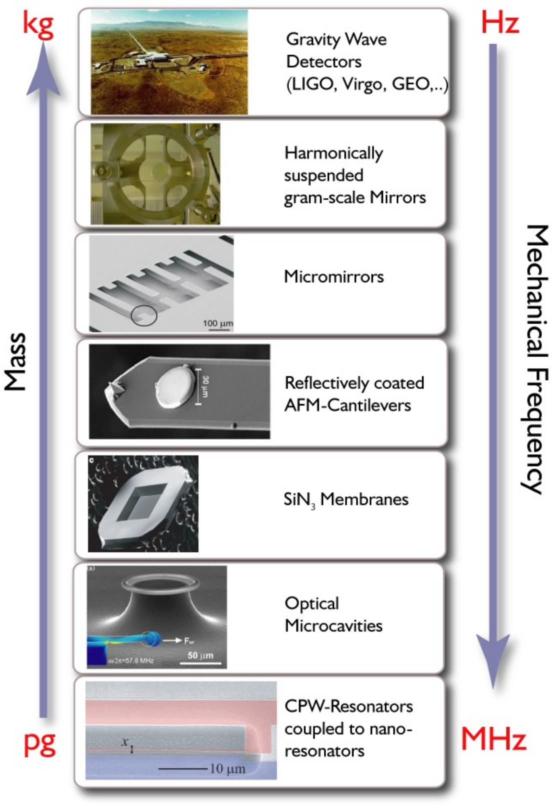
Carmon, Roksari, Kippenberg, Vahala, **PRL 94**, 223902 (2005).
Kippenberg, Roksari, Carmon, Scherer, Vahala, **PRL 95**, 033901 (2005).
Rokhsari, Kippenberg, Carmon, Vahala, **Opt. Exp. 13**, 5293 (2005).

Optomechanical Cooling



Schliesser, et al, Vahala, Kippenberg, PRL 97 (2006)
Arcizet, Cohadon, Briant, Pinard, Heidmann, Nature 444, 71 (2006)
S. Gigan et al., Nature 444, 67 (2006)

Multi order-of-magnitude Range of Size Scales and Frequencies

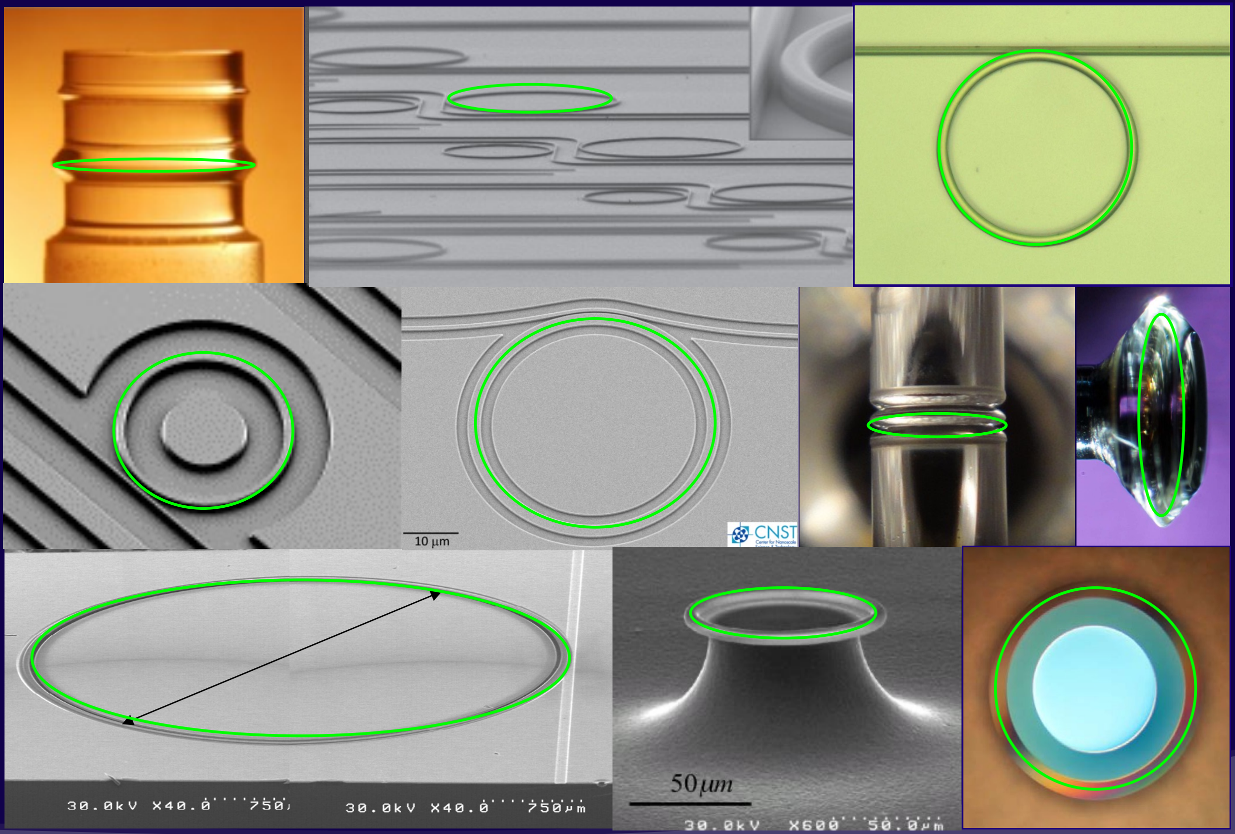


Kippenberg, Vahala, Science (2008)

Moving forward towards present day

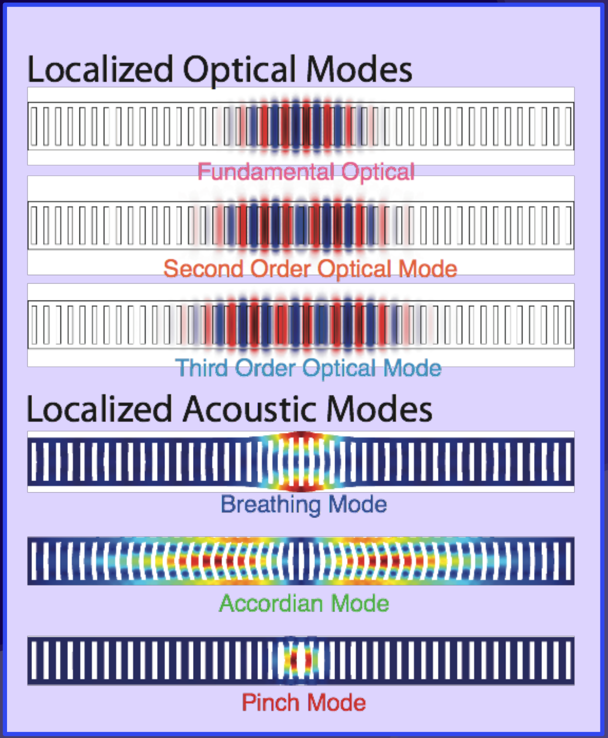
More materials and addition of integrated waveguide coupling

Silica, silicon nitride, silicon, Mg/Ca F_2, aluminum nitride, diamond.....



Not Discussed

Photonic Crystal Resonators
Optomechanical Crystals



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Scientific studies have greatly expanded since these early works. Modern focus areas include quantum optics and quantum information.

- Recent Progress (Technology and Integration):
  - Optical Gyroscopes
  - Miniature frequency combs
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Trends:
- Greater levels of integration
- Increasing Performance
- Low SWAP

- Outlook

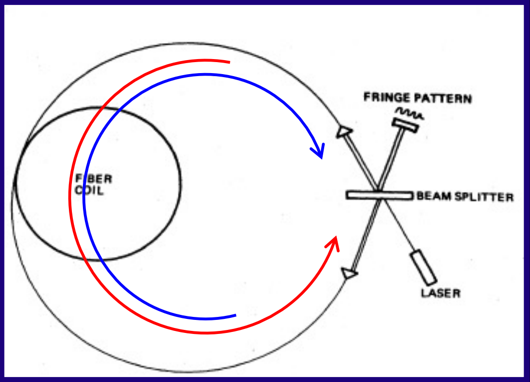
A CHIP-BASED BRILLOUIN GYROSCOPE

Commercial Optical Gyros

- Two versions:
  - **Non-resonant device:** optical path difference
  - **Resonant device:** optical frequency difference
- High performance & no moving parts
- Large in comparison to MEMs gyros & not integrable in their current versions

Non-resonant gyros

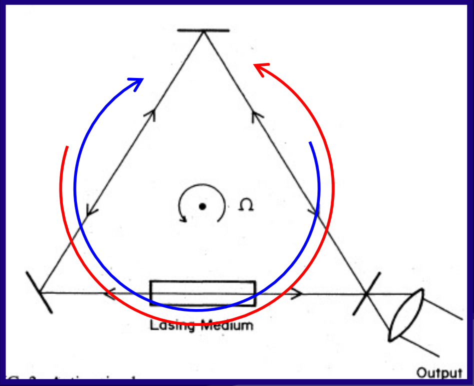
- Fiber optic gyros (FOG)
- Create huge physical path length for CW and CCW waves



$$\delta\phi = \frac{8\pi \mathbf{A}\cdot\mathbf{\Omega}}{\lambda c}$$

Resonant gyros

- Ring laser gyro (RLG)
- Create huge \`effective' path length for CW and CCW waves



$$\delta\nu = \frac{4\mathbf{A}\cdot\mathbf{\Omega}}{\lambda P}$$

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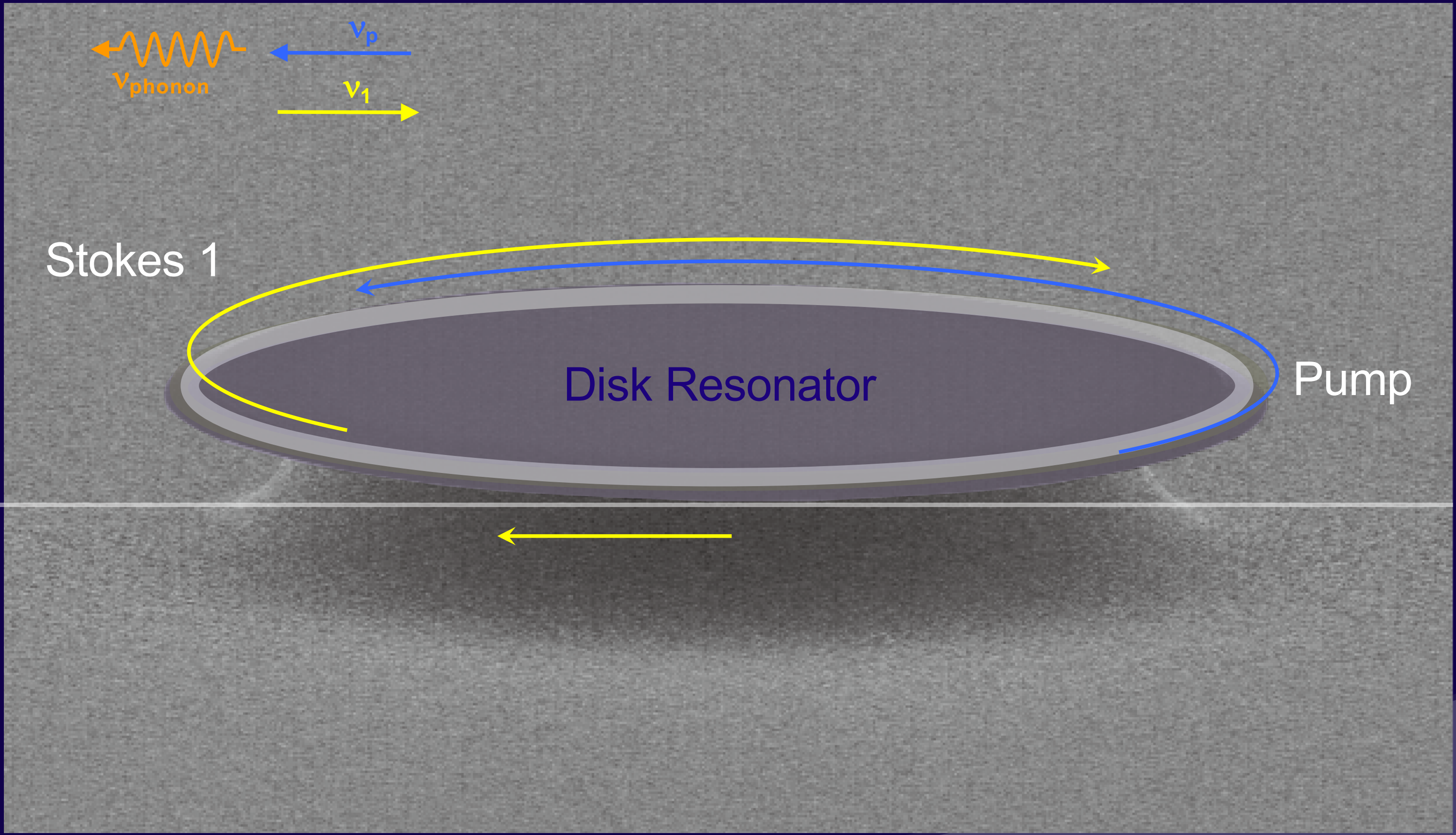
Brillouin Laser Action



Tomes, Carmon, Phys. Rev. Lett. (2009)
Grudinin, et. al. Maleki, Phys. Rev. Lett. (2009)
H. Lee, et. al, Vahala, *Nature Photonics* (2012)

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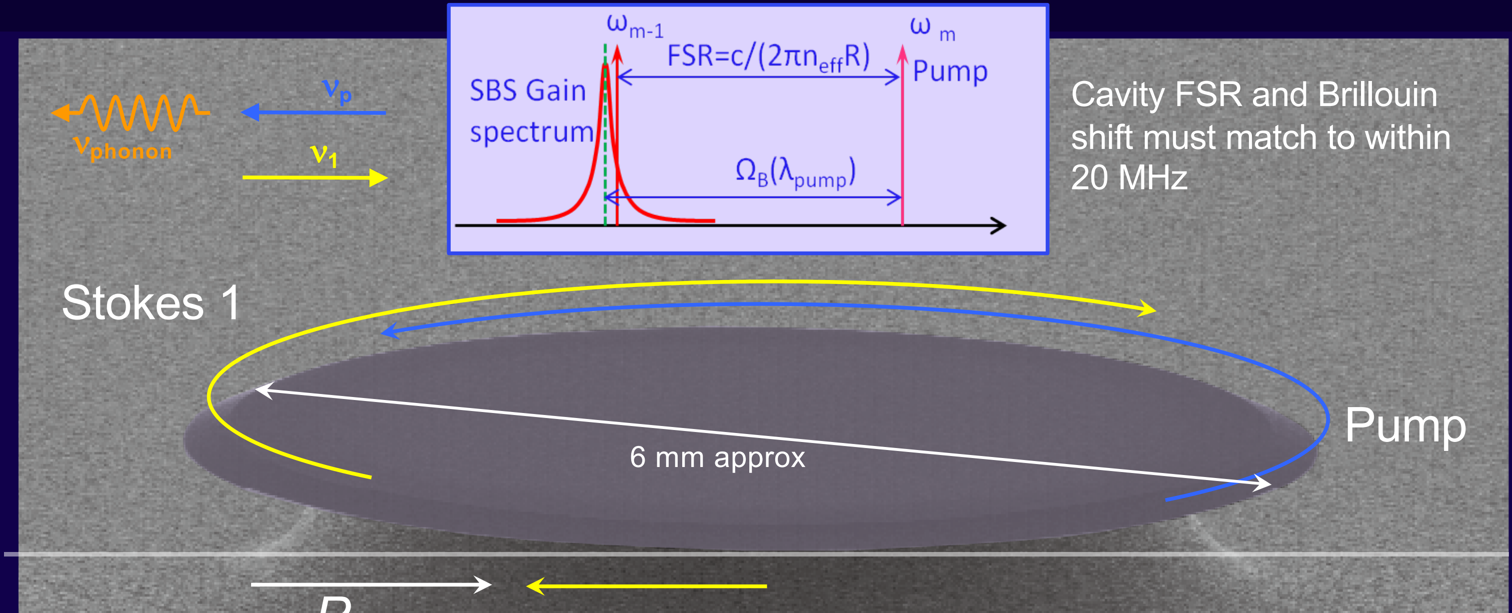
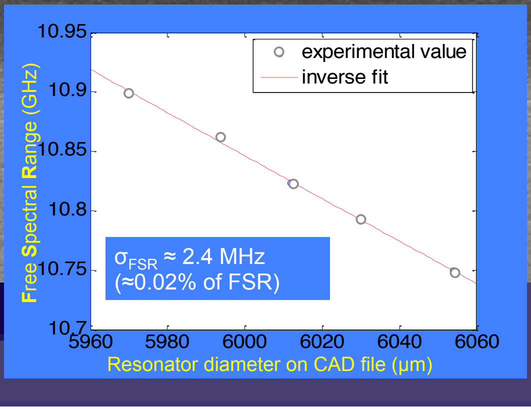
Phase Matching of Brillouin : Lithographic Control



Cavity FSR and Brillouin shift must match to within 20 MHz



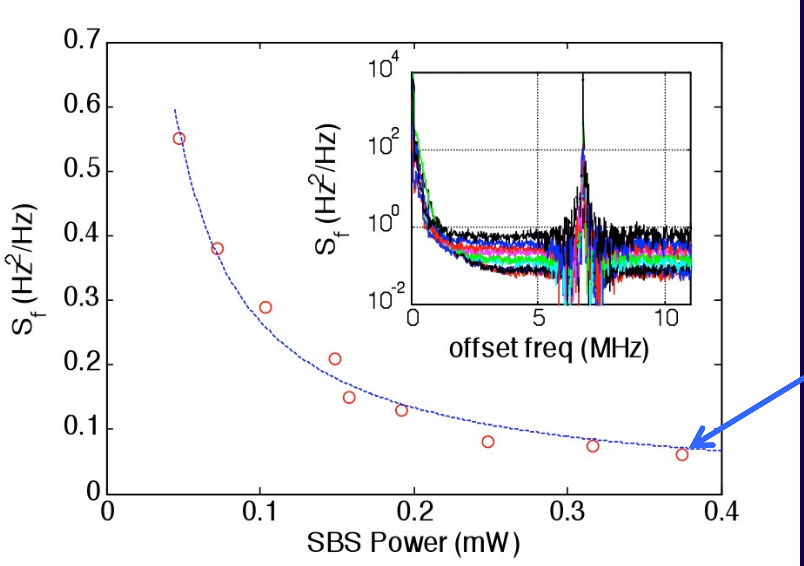
Lithographic control of cavity size enable precise phase matching control

High-Q: Very low fundamental frequency noise

Schawlow-Townes-like linewidth of the Brillouin laser [1,2]:

$$S_{\nu}^{ST}(f) = \frac{\hbar\omega^3}{8\pi^2 P Q_T Q_{ex}}(n_T + N_T + 1)$$

S-T noise varies inverse quadratic with Q factor and inversely with power.



Lowest frequency noise of any chip-based laser [1]

0.06 Hz^2/Hz minimum ST frequency noise

[1] H. Lee, T. Chen, J. Li, K. Yang, S. Jeon, O. Painter and K. J. Vahala, Nat. Photon. 6, 369--373 (2012).
[2] J. Li, H. Lee, T. Chen, and K. J. Vahala, Opt. Exp. 20, 20170-20180 (2012).

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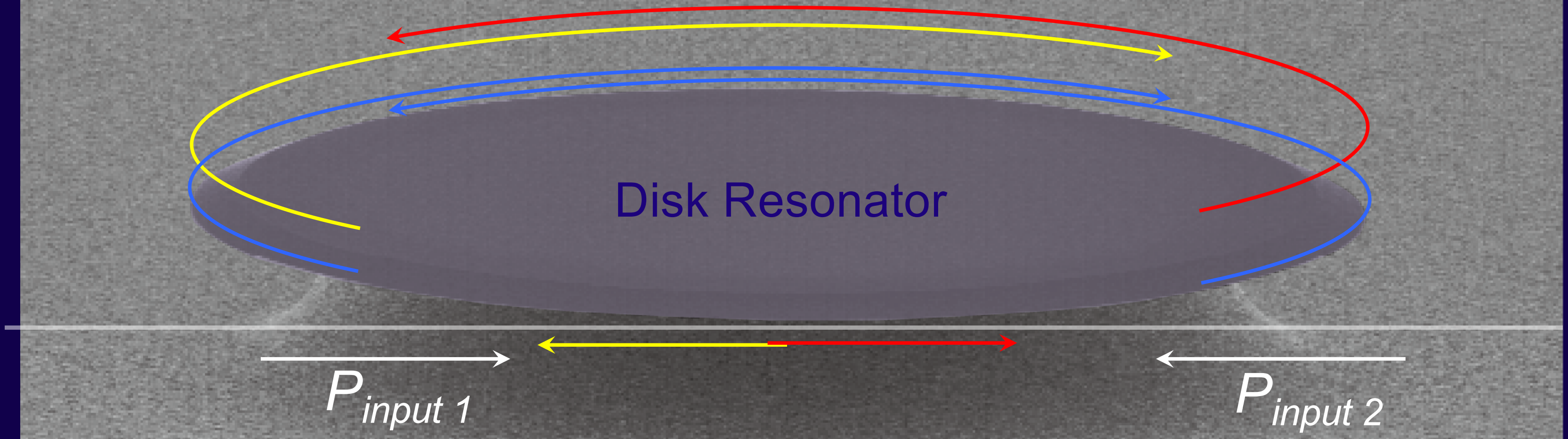
Counter-pumped near-degenerate operation

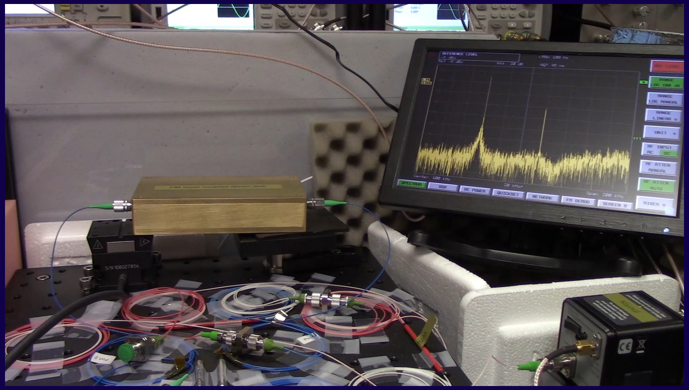
- Counter-pumping on the same resonator mode induces CW and CCW laser operation.
- The resulting CW and CCW laser frequencies are separated by an audio-frequency rate and also share the same longitudinal mode of the resonator.
- A single pump is still used.

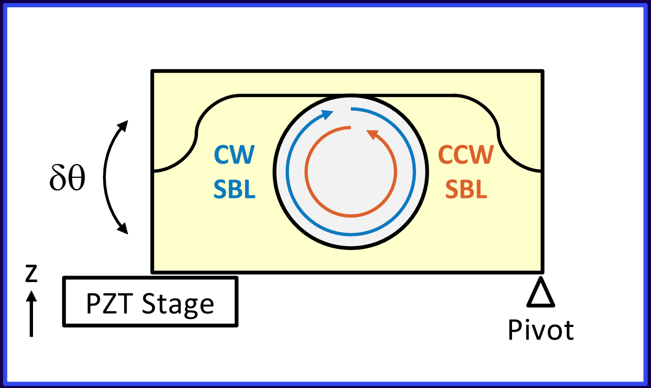


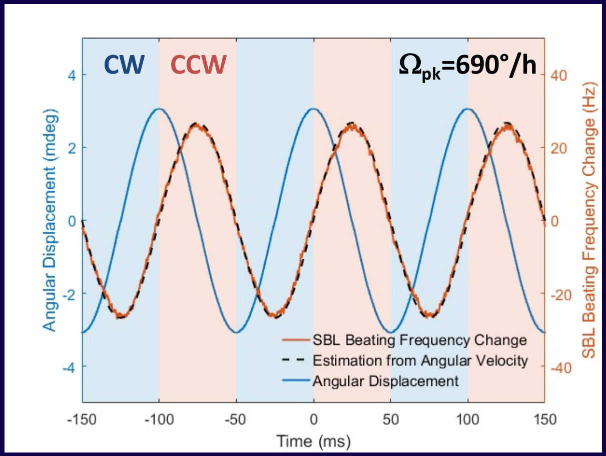
- However, these frequencies will lock.
- Can be prevented by detuning the pump frequencies.

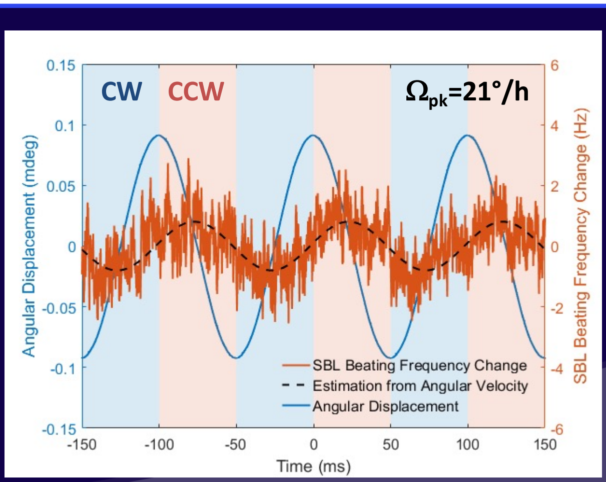
Lai, et. al., Vahala, Nature (2019)

Gyro readout under rotation



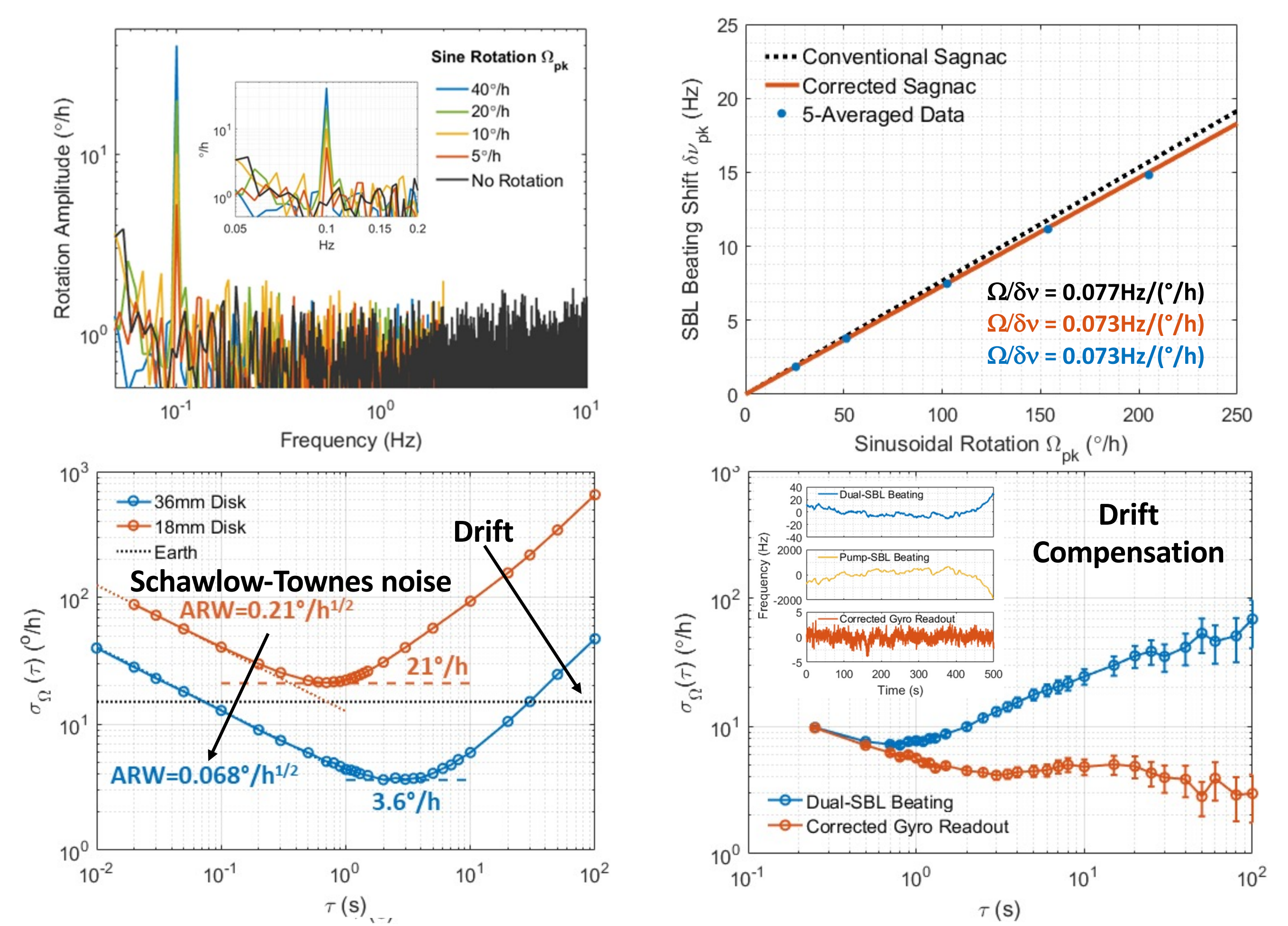






Lai, et. al., Vahala, Nature Photonics (2020)

Allan Deviation & Drift Correction



Lai, et. al., Vahala, Nature Photonics (2020)

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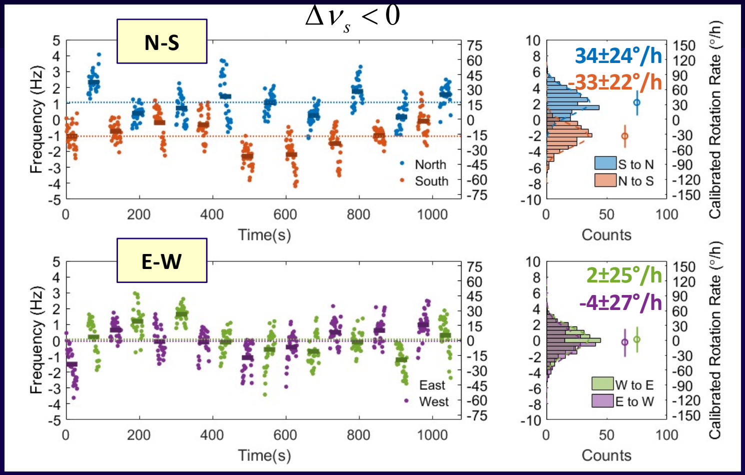
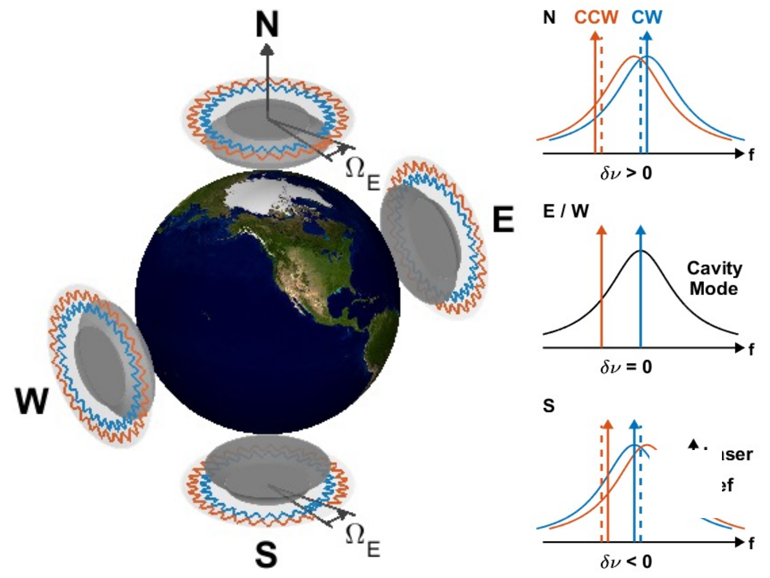
Earth Rotation Measurement





Lai, et. al., Vahala, Nature Photonics (2020)

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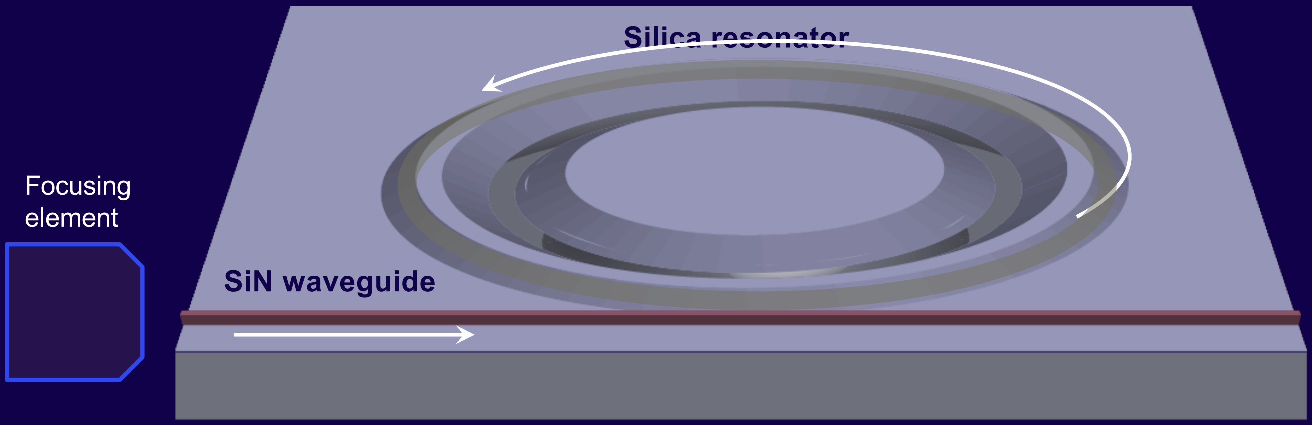
Integrated Waveguide Brillouin Laser

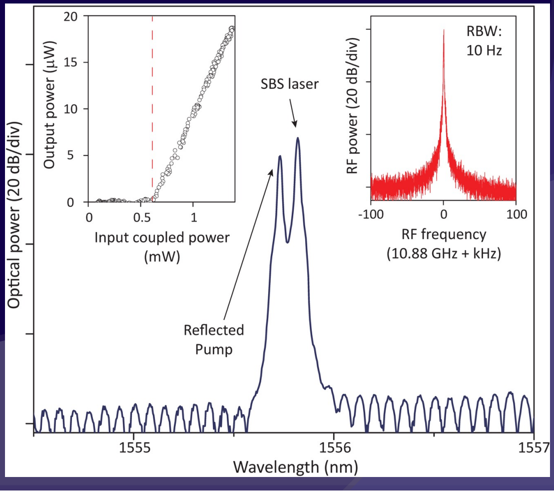
K. Y. Yang *et. al*, Vahala *Nat. Photonics* (2018)



Silica resonator

Focusing element

SiN waveguide



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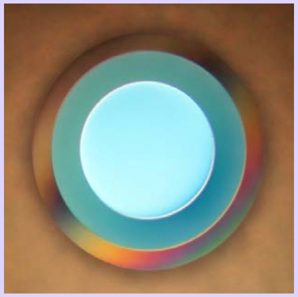
Recent Demonstrations

Microresonator Brillouin Gyroscope



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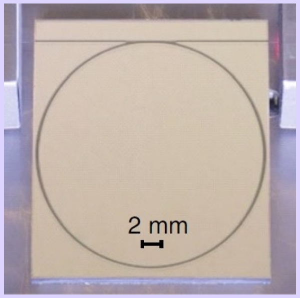
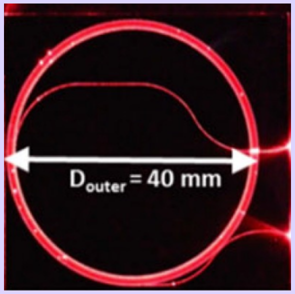
Li, Suh, Vahala, Optica **4** (2017)
Lai, et. al., Vahala, Nature Photonics (2020)



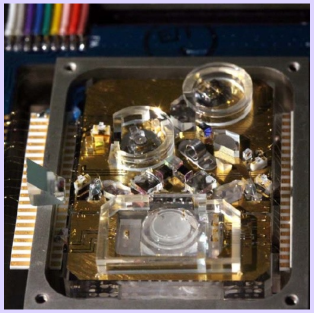
UCSB, Honeywell
Gundavarapu, et. al., Blumenthal
Nature Photonics **13** (2019)

Integrated Interferometric Optical Gyroscope

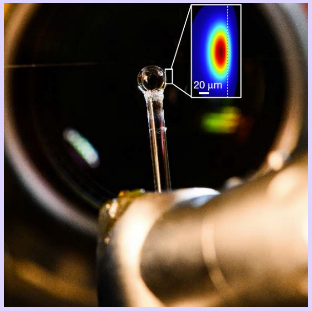


UCSB
Gundavarapu, et. al.,
J. Light. Technol. **36** (2018)

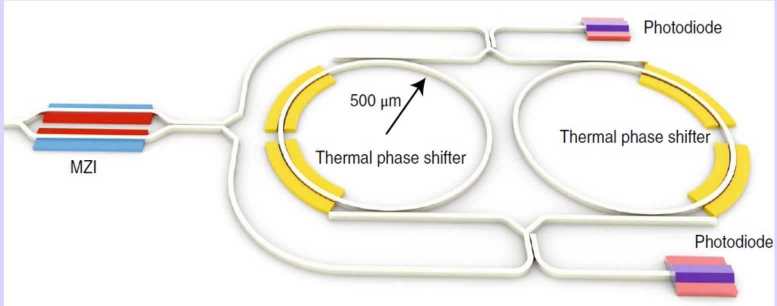
Resonator Micro Optic Gyroscope



OEwaves
Liang, et. al., Maleki,
Optica **4** (2017)



Technion
Maayani, et. al., Carmon,
Nature **558** (2018)



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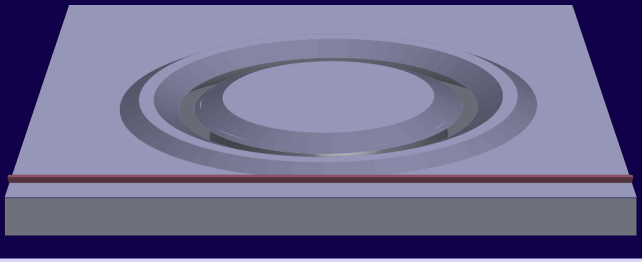
Khial, et. al., Hajimiri,
Nature Photonics **12** (2018)

FREQUENCY MICROCOMBS

Soliton Microcombs

Frequency Microcomb



Coherently pumped soliton pulses
- High Q very important
- Kerr effect provides soliton confinement and parametric gain
- Self-referencing demonstrated

Coherent soliton Proposal

Wabnitz, *Optics Lett.* (1993)

Parametric oscillation & cascaded FWM in microcavities

Kippenberg, .. Vahala, *Phys. Rev. Lett.* (2004)
Savchenkov, .. Maleki, *Phys. Rev. Lett.* (2004)

Cascaded Microcomb

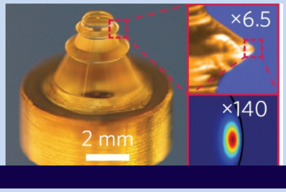
Del Haye … Kippenberg, *Nature* (2007)

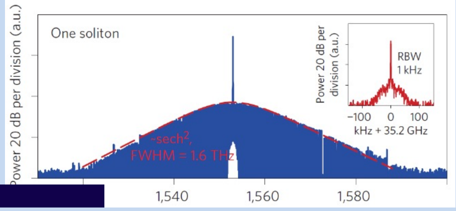
Coherent pumped soliton

Leo, et. al., *Nature Photonics* (2010)

Early Soliton Microcombs

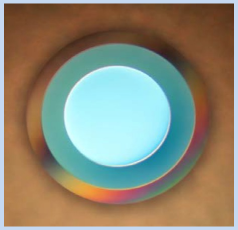
MgF_2

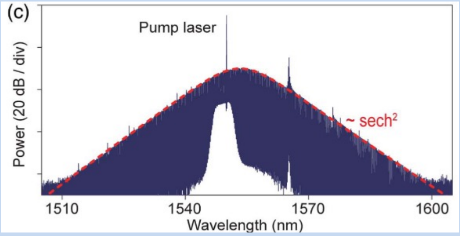




EPFL, Moscow state [1]

Silica





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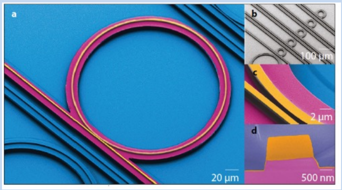
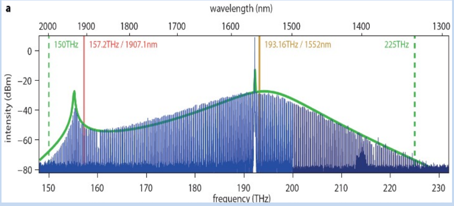
Si_3N_4





EPFL [3] , Purdue [4], Columbia [5]

1. Herr et al.Kippenberg, Nat. Photonics 8, 145 (2014).
2. Yi,. et. al., Vahala, Optica 2, 1078 (2015).
3. Brasch et al. Kippenberg, Science 351, 357 (2016).
4. Wang et al. Weiner, Opt. Express 24, 10890 (2016).
5. Joshi et al. Gaeta, Opt. Lett. 41, 2565 (2016).

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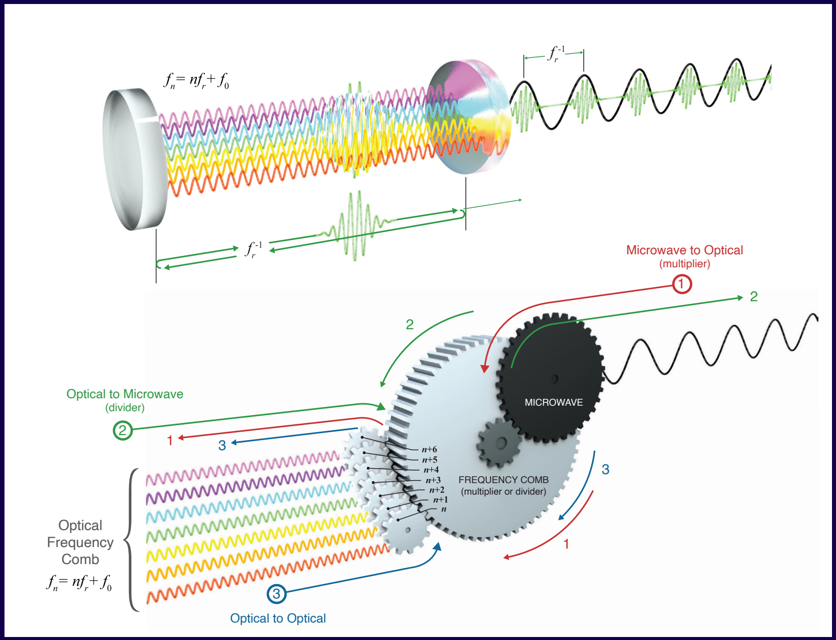
Mechanical Analogy of Self Referenced Frequency Comb

Hänsch & Hall

Nobel Prize 2005

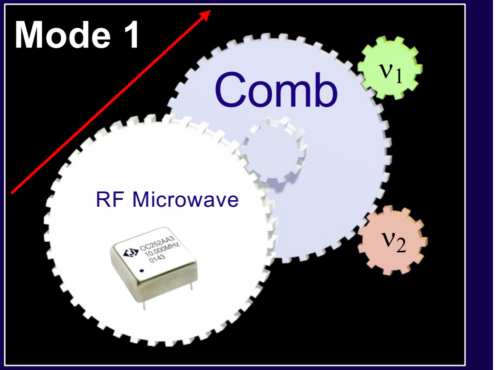
- T. W. Hänsch, Nobel lecture: Passion for precision. Rev. Mod. Phys.78, 1297–1309 (2006).
- J. L. Hall, Nobel lecture: Defining and measuring optical frequencies. Rev. Mod. Phys. 78, 1279–1295 (2006).

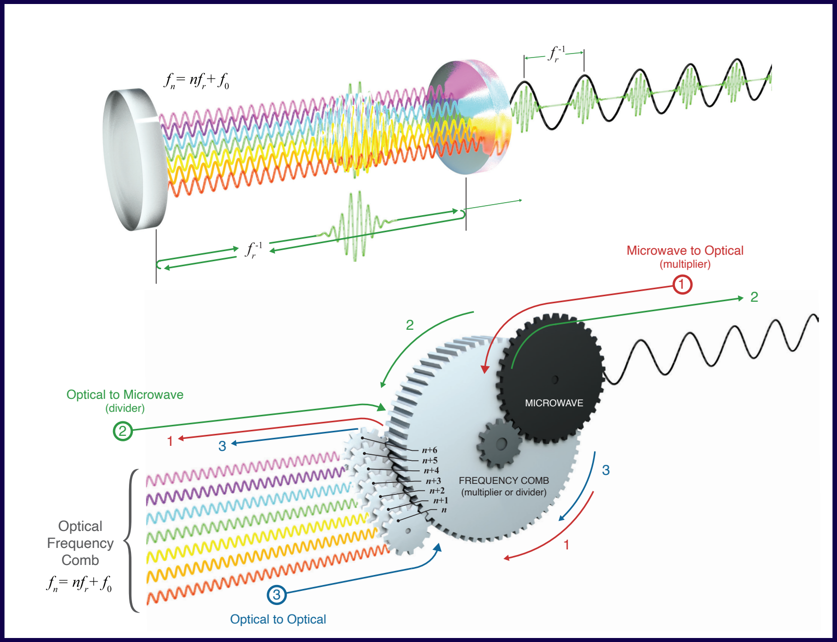


- Mode locked pulses are phase synchronized with optical fields
- Three modes of operation possible:
  1. Microwave to optical (Frequency synthesis)
  2. Optical to microwave (Frequency division)
  3. Optical to optical (Frequency translation)

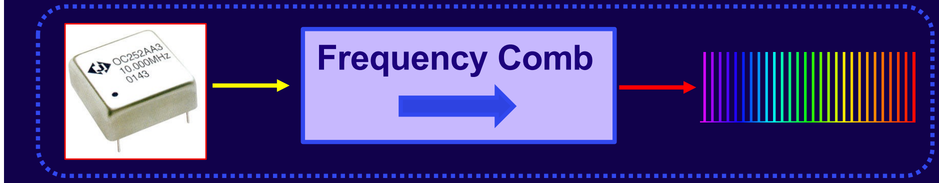
Diddams, Vahala, Udem, Science (2020)

Frequency Synthesis Mode





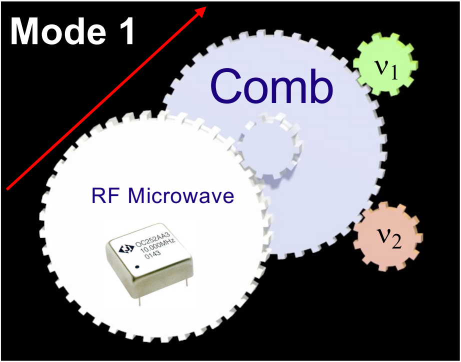
Optical Frequency Synthesis

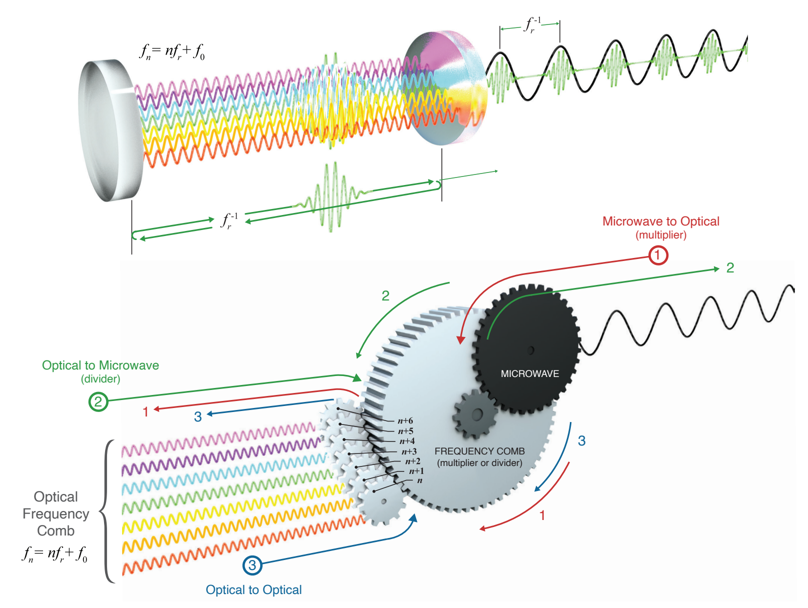


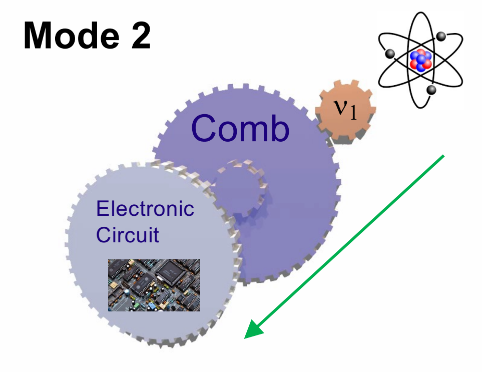
D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," Science 288, 635–639 (2000).

Diddams, Vahala, Udem, Science (2020)

Optical Frequency Division Mode

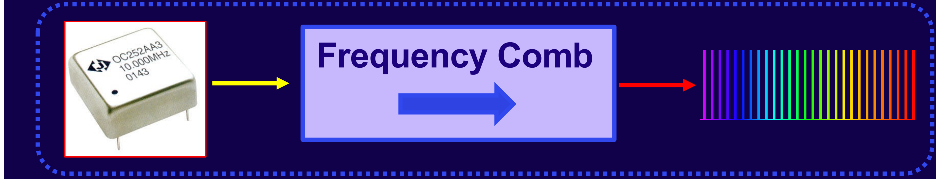




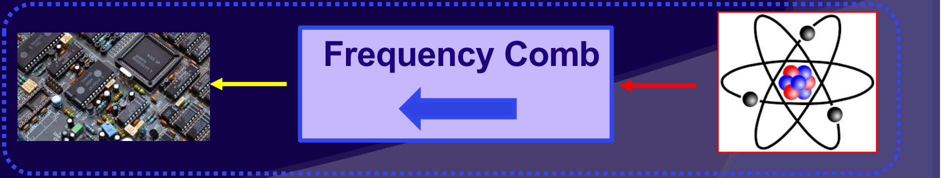


Optical Frequency Synthesis

Most Accurate Clocks
&
Lowest Noise Oscillators



Frequency Comb



Frequency Comb

D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," Science 288, 635–639 (2000).

- **Clock:** S. A. Diddams, Th. Udem, J. C. Bergquist, E. A. Curtis, R. E. Drullinger, L. Hollberg, W. M. Itano, W. D. Lee, C. W. Oates, K. R. Vogel, D. J. Wineland, "An Optical Clock Based on a Single Trapped 199Hg+ Ion," Science 293, 825 (2001)
- **Microwave:** T. M. Fortier, M. S. Kirchner, F. Quinlan, J. Taylor, J. C. Bergquist, T. Rosenband, N. Lemke, A. Ludlow, Y. Jiang, C. W. Oates and S. A. Diddams, "Generation of ultrastable microwaves via optical frequency division," Nature Photonics 5, 425 (2011)

Diddams, Vahala, Udem, Science (2020)

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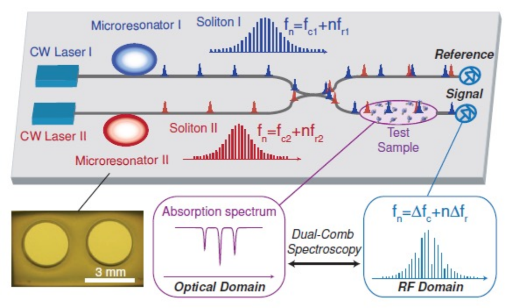
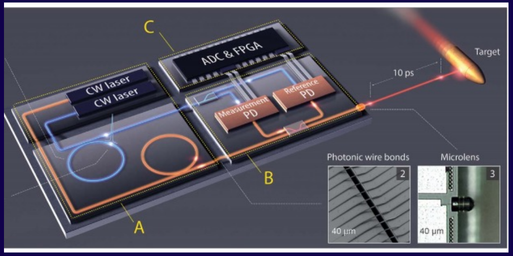
Many Applications Being Investigated:
Long term - All could ultimately be miniaturized

Dual comb spectroscopy



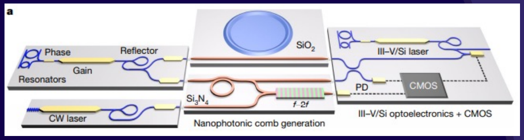
Suh, Yang, Vahala, *Science* (2016)
Dutt, et. al., Gaeta, *CLEO* (2017)

Dual Comb Lidar



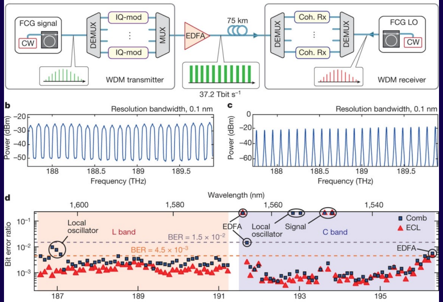
Suh, Vahala, *Science* (2018)
Trocha, et. al., Koos, *Science* (2018).
Riemensberger et al, Kippenberg, Nature (2020)

Optical Frequency Synthesis



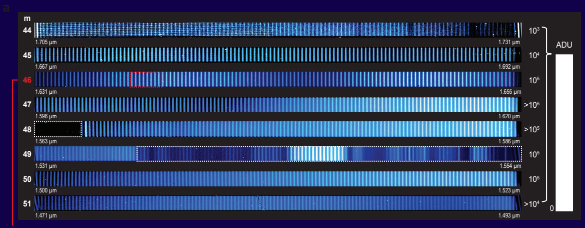
Spencer, et. al., Papp, *Nature* (2018)

Data transmission



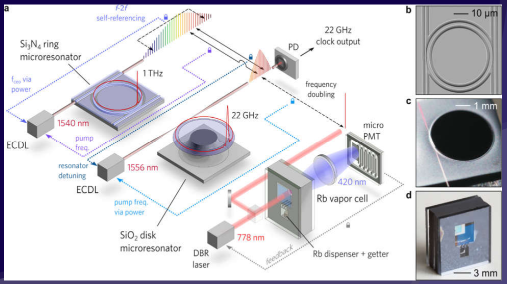
Marin-Palomo, et al. Koos, *Nature* (2017)
Mazur, et. al. Andrekson, arXiv:1812.11046 (2018)

Exoplanet Detection
(`Astrocomb')



Obrzud, et. al., Herr, *Nat. Phot.* (2019)
Suh, et. al, Vahala, *Nat. Phot.* (2019)

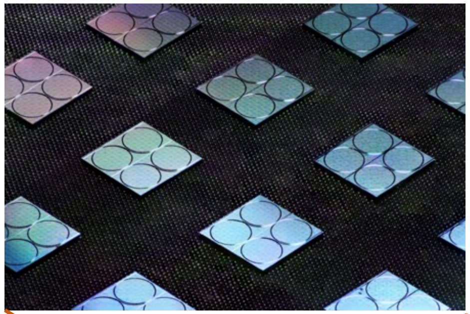
Optical Clock



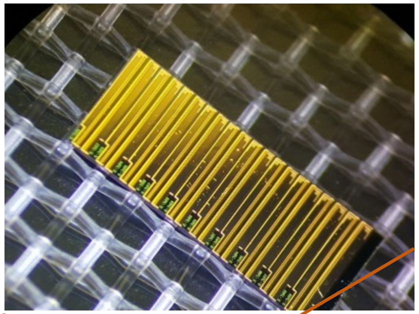
Newman, et. al., Hummon, *Optica*, (2019)

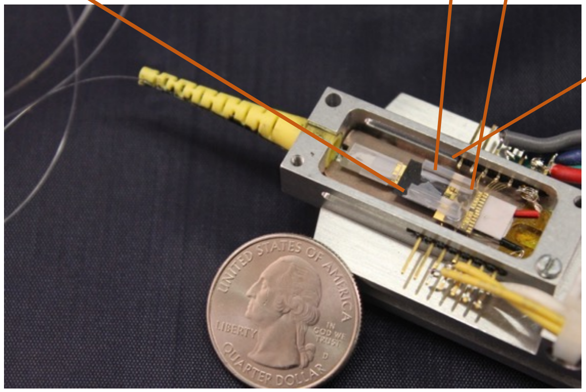
Integrated Turnkey Soliton Microcomb

High Q SiN resonator (EPFL)



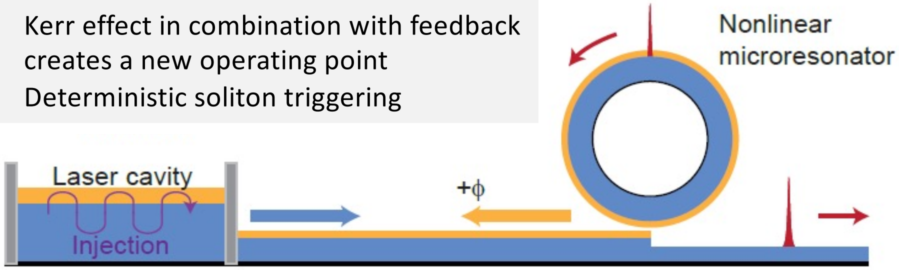
High power DFB (UCSB)

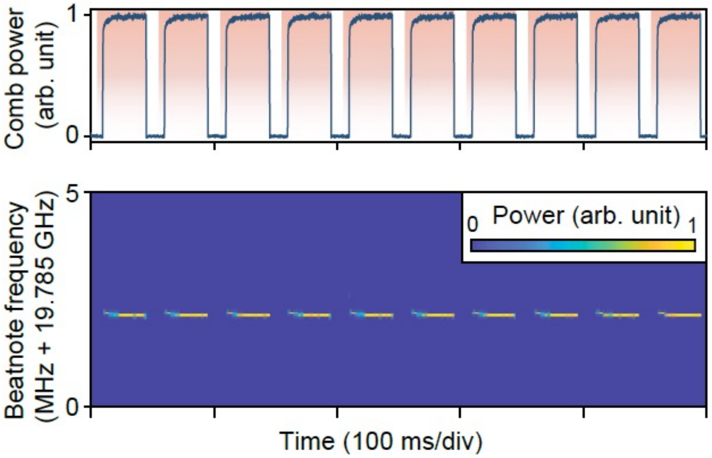




Turnkey operation

- No isolator
- Kerr effect in combination with feedback creates a new operating point
- Deterministic soliton triggering



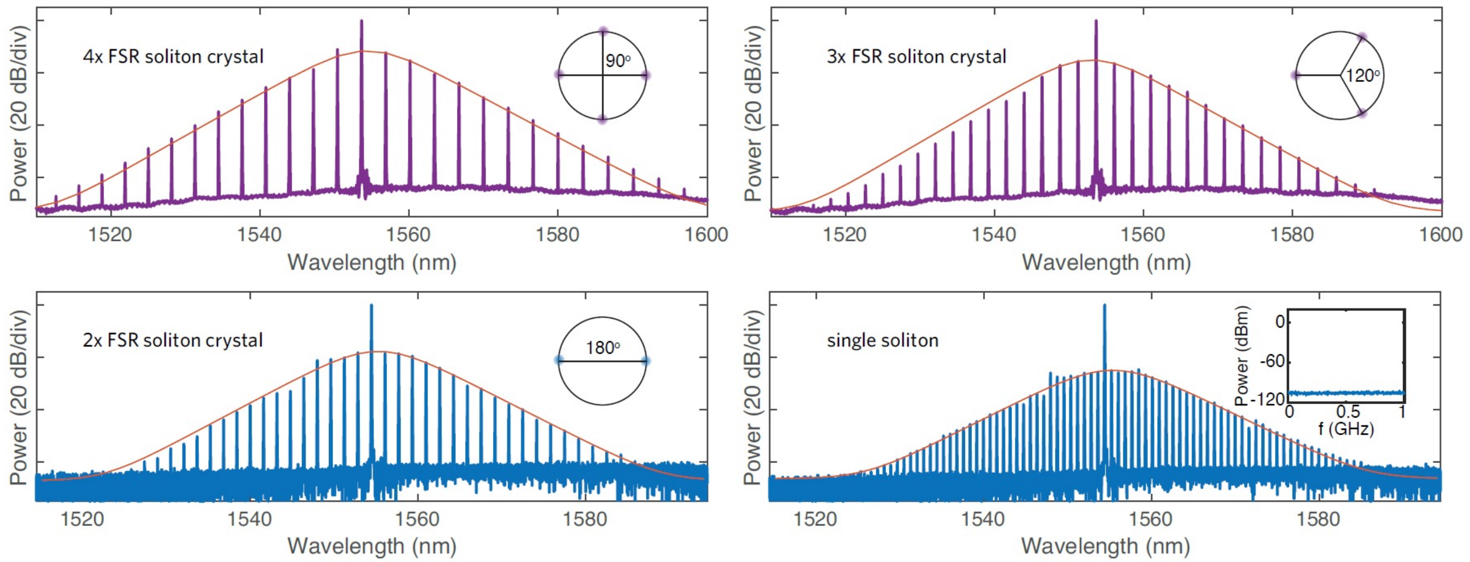


Turnkey microcomb: Shen, Chang, Liu … Kippenberg, Vahala and Bowers, *Nature* 582, 365 (2020)

Battery operated microcomb: Stern, et al., Gaeta & Lipson, *Nature* (2018)

Self-injection locked microcomb: Liang, et. al., Maleki, Nat. Commun. 6, 7957 (2015)

Heterogeneous integration of laser soliton microcombs

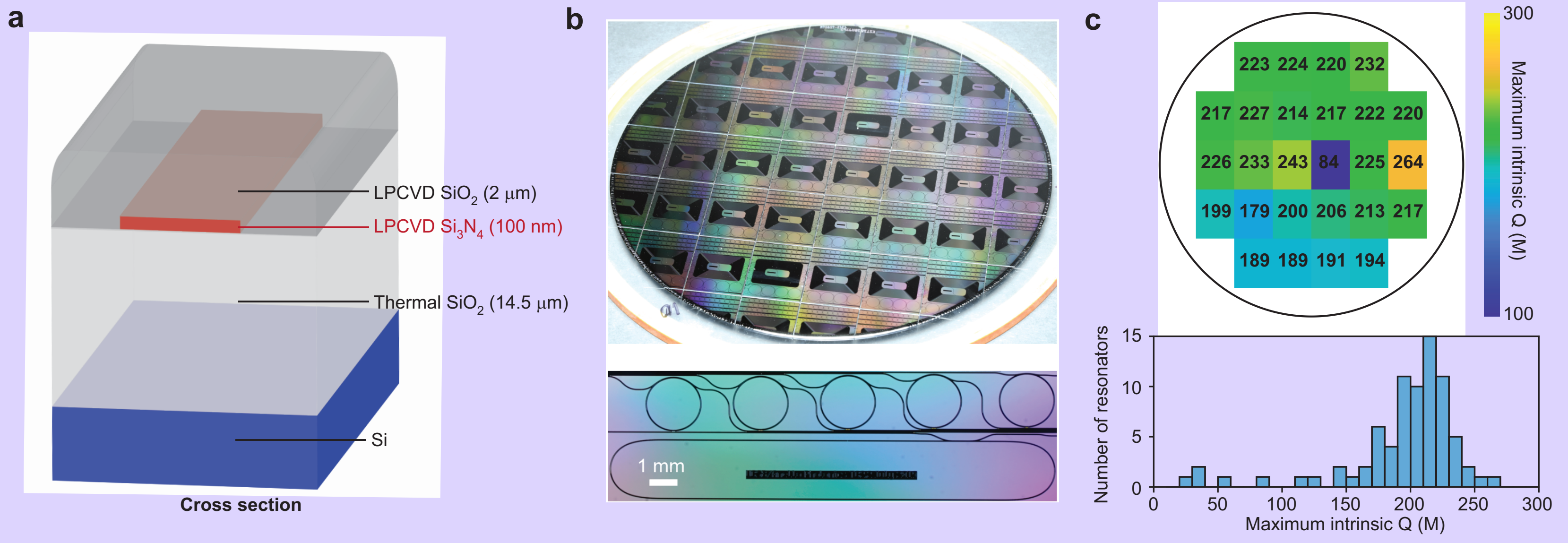


- Current initiated and controlled soliton generation
- Soliton states dependent on the laser-resonance detuning, controlled by laser current and phase tuner current
- Manually tuned into soliton states, without feedback or sweep
- Very stable soliton without feedback, hours operation in lab environment

Xiang, Liu,…, Kippenberg, Bowers, ‘Laser soliton microcombs heterogeneously integrated on silicon’, Science 2021

Foundry-made UHQ Resonators

Ultra-high-Q resonators on an 8-inch foundry wafer with high yield

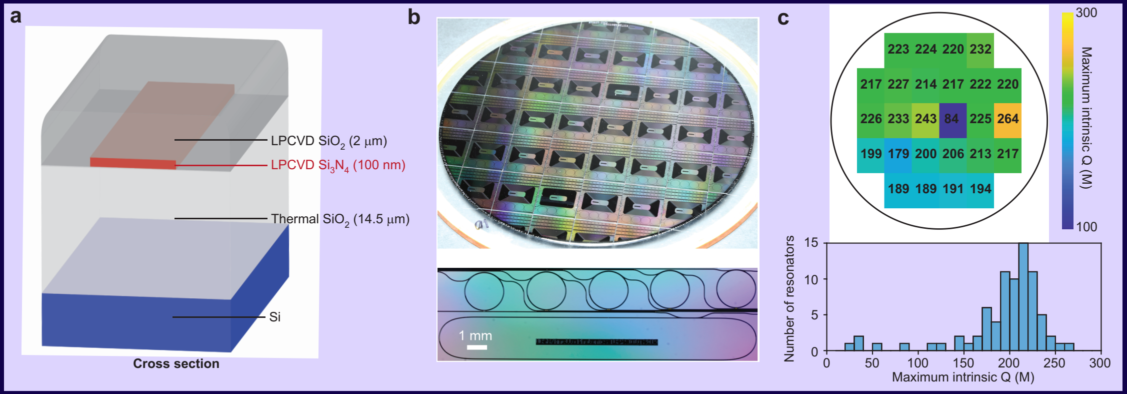


Jin, et. al. ….. Paniccia, Vahala and Bowers, *Nature Photonics* (2021)

Also see: Puckett, et al…… Blumenthal, *Nature Communications* (2021)

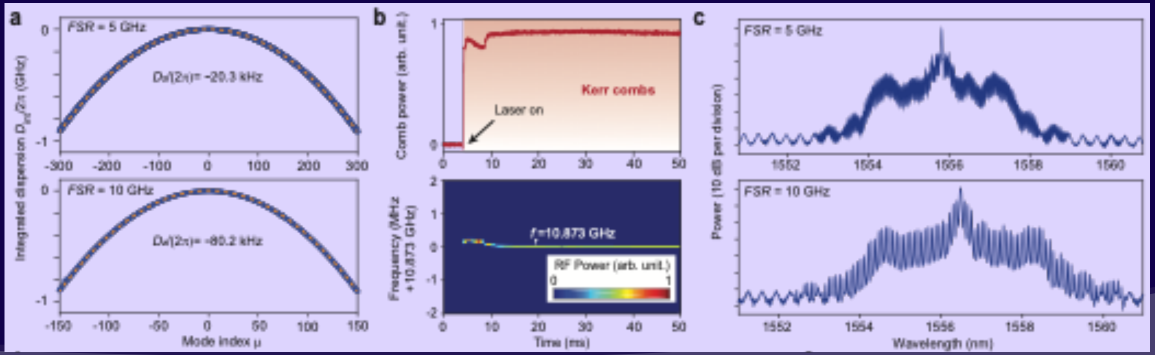
Turnkey microcombs with normal dispersion

UHQ on an 8 inch wafer with high yield



W. Jin, et. al. ….. K. Vahala and J. Bowers, *Nature Photonics* (2021)
M. Puckett, et. al.,….D. Blumenthal, *Nature Comm.* (2021)

Turnkey soliton generation

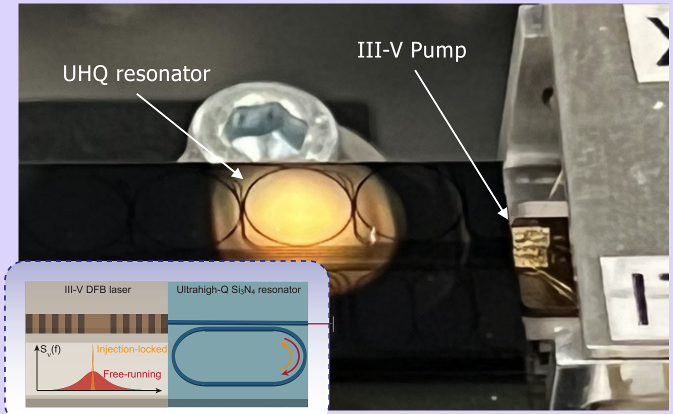


W. Jin, et. al. ….. K. Vahala and J. Bowers, *Nature Photonics* (2021)

Turnkey operation of dark soliton microcomb

- No isolator. Easily packaged.
- Deterministic triggering
- Kerr nonlinearity in combination with feedback creates a self-regulation process that generates pulse train with near 50% duty cycle*
- Duty cycle is optimal for higher microwave powers

UHQ resonator directly coupled to pump



UCSB

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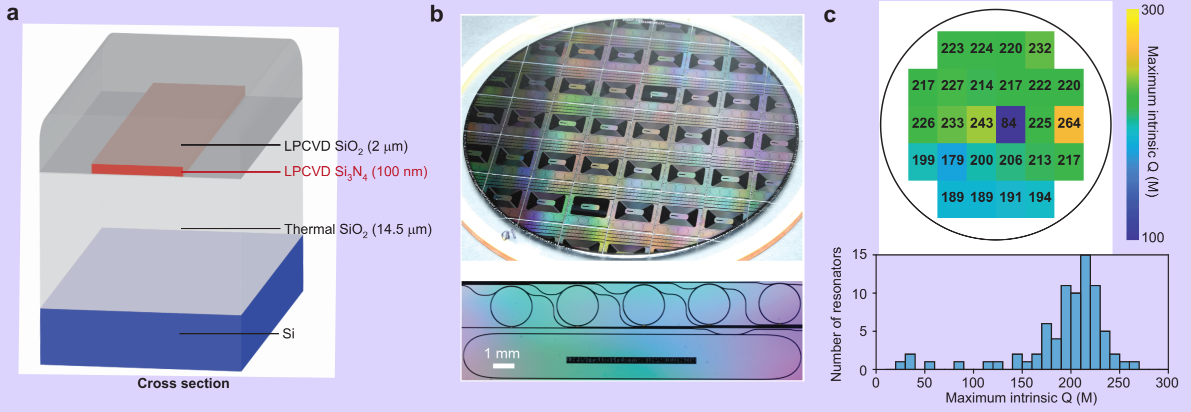
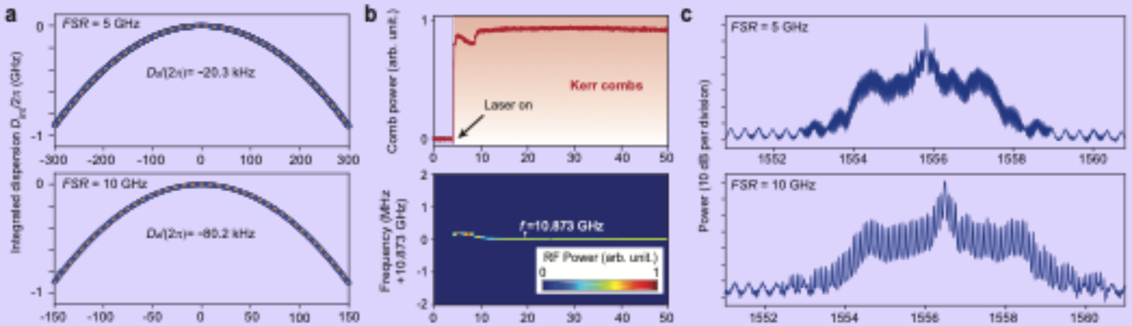
Self-injection locking: high coherence

UHQ on an 8 inch wafer with high yield

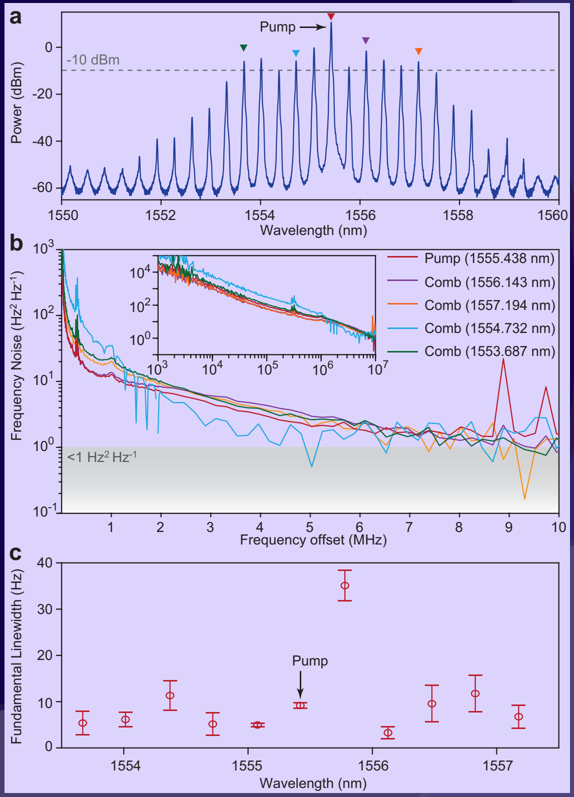


Turnkey dark soliton generation



W. Jin, et. al. ….. K. Vahala and J. Bowers, *Nature Photonics* (2021)

Narrow linewidth pump distributed over microcomb lines



HIGH COHERENCE SOURCES

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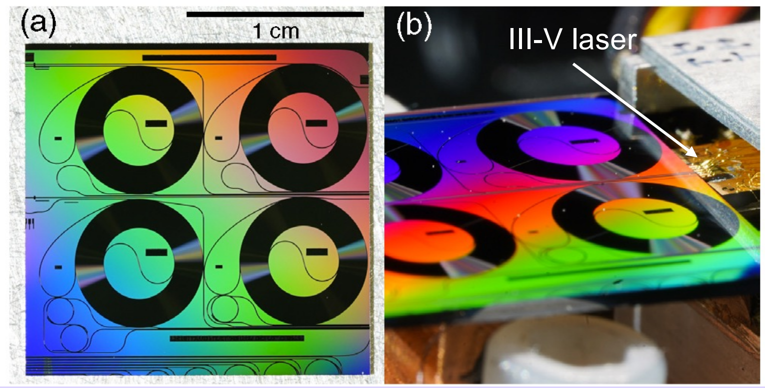
Frequency noise exceeding high performance fiber lasers

High-Q spiral resonators

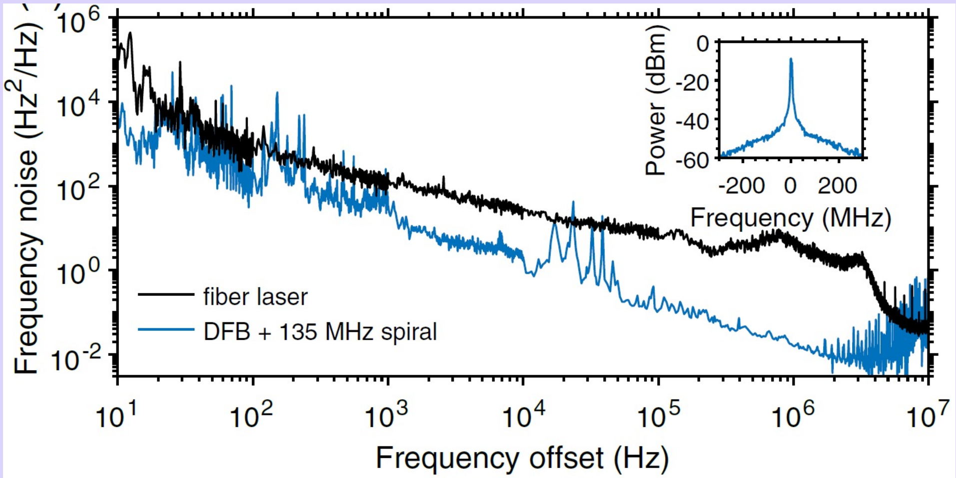


- 1.4-meter-long spiral resonator
- 160M intrinsic Q
- 70 dB frequency noise reduction
- 0.04 Hz short-term linewidth
- Large reduction of thermo-refractive noise (TRN)

Li, Jin, …, Vahala, Bowers. Reaching fiber-laser coherence in integrated photonics. Optics Letters. 2021

Spiral resonator features large mode volume and high Q factor

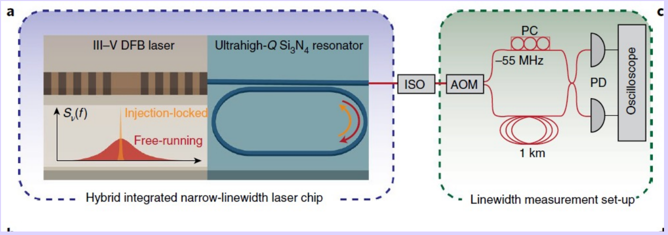
- High Q factor suppresses short term noise (equivalently, noise at high offset frequencies)
- Large mode volume suppresses TRN noise so that low offset frequency noise is very low.

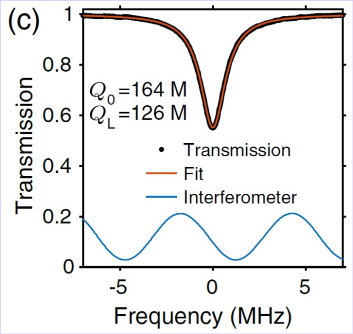


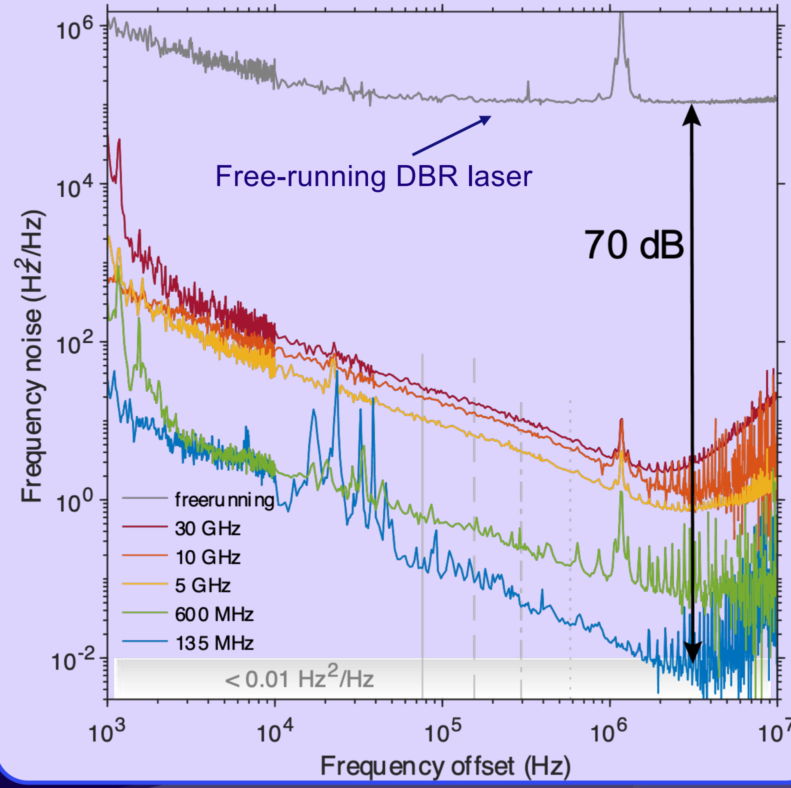
Self-injection-locking using ultra-high-Q spiral resonators

Ultra-high-Q spiral resonators for self-injection locking (SIL)

- 1.4-meter-long spiral resonator
- 160M intrinsic Q
- 70 dB frequency noise reduction
- 0.04 Hz short-term linewidth
- Large reduction of thermo-refractive noise (TRN)







Li, Jin, …, Vahala, Bowers. Reaching fiber-laser coherence in integrated photonics. Optics Letters. 2021

Strong suppression of TRN noise from large mode volume

Ultra-high-Q spiral resonators for self-injection locking (SIL)

- 1.4-meter-long spiral resonator
- 160M intrinsic Q
- 70 dB frequency noise reduction
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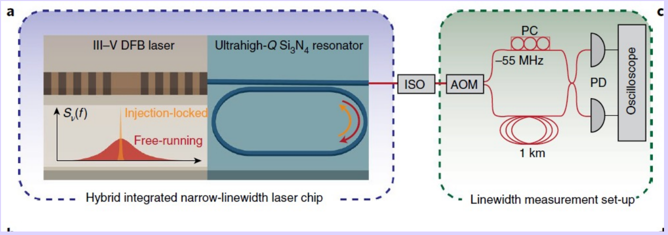
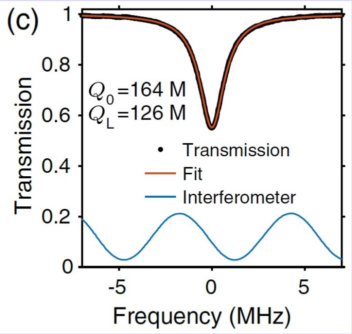
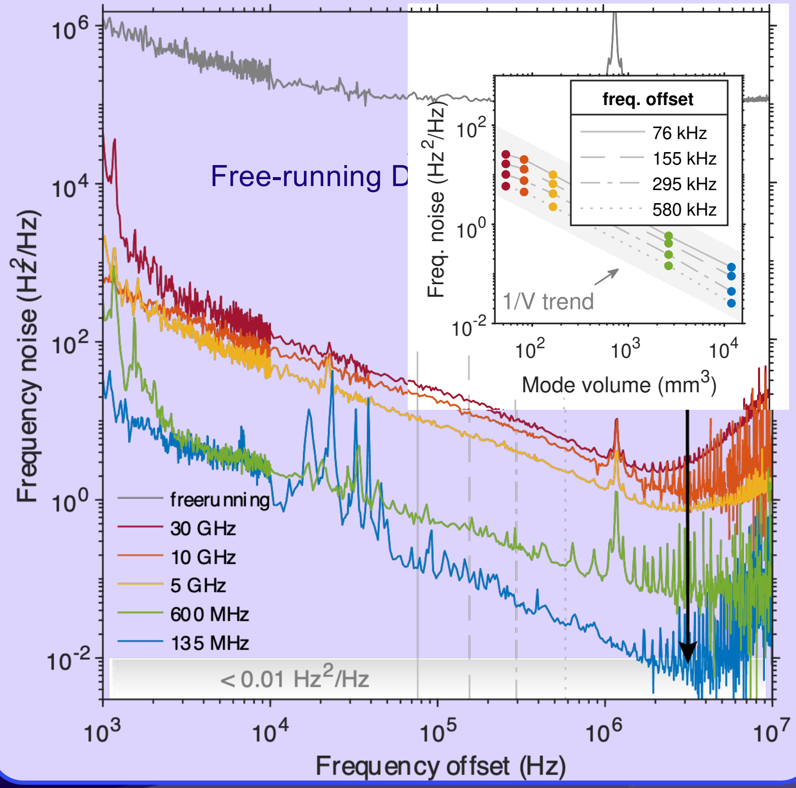
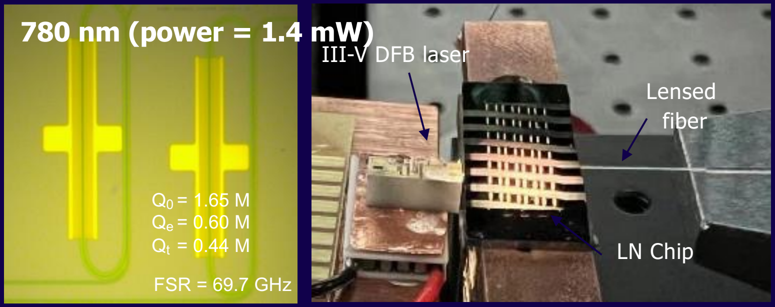


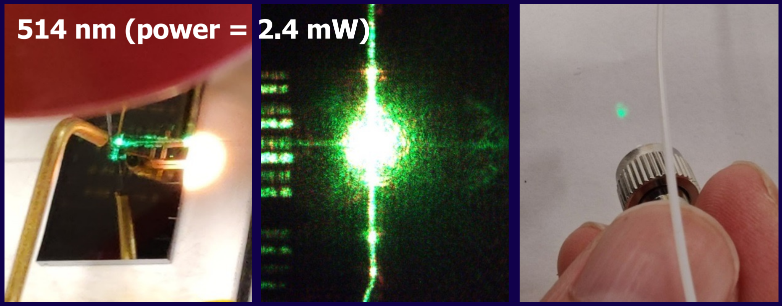


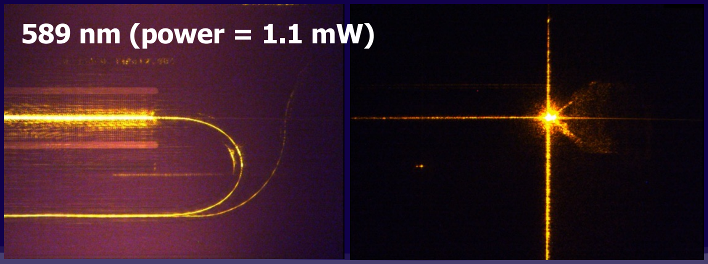


Li, Jin, …, Vahala, Bowers. Reaching fiber-laser coherence in integrated photonics. Optics Letters. 2021

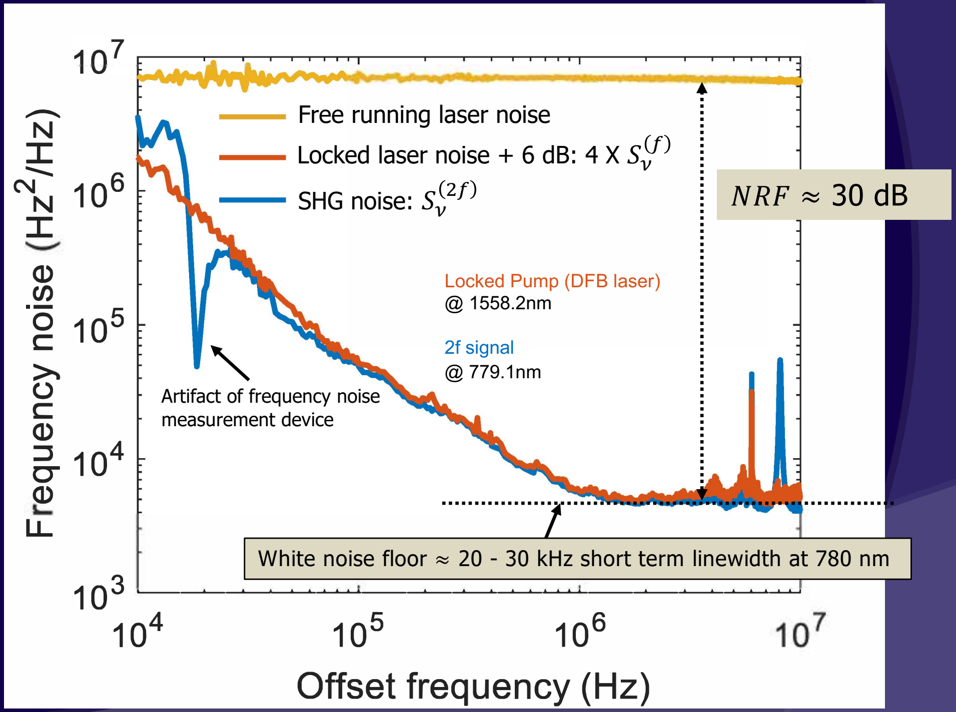
High-Q Thin-Film Lithium Niobate Microresonators for High-coherence visible band generation


780 nm (power = 1.4 mW)


514 nm (power = 2.4 mW)


589 nm (power = 1.1 mW)

SHG frequency noise measurement
DFB laser self-injection locked to lithium niobate resonator



Staffa, et al, Bowers, Vahala, Lin, CLEO 2022

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Xu Yi (U. of Virginia)
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Lin Chang (UCSB)
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OUTLOOK

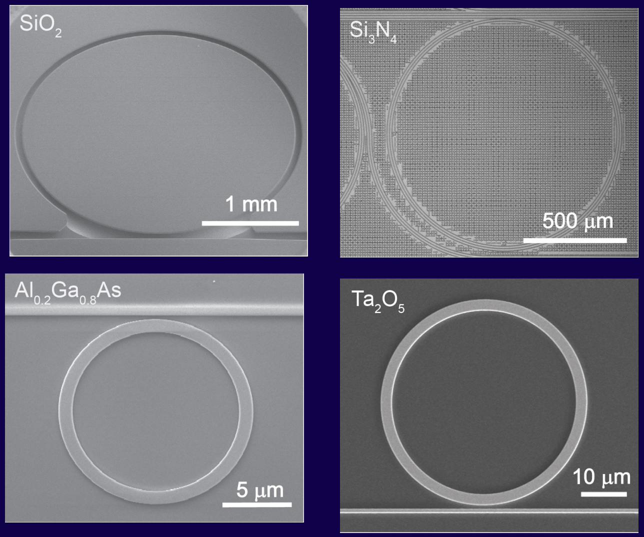
Opportunities

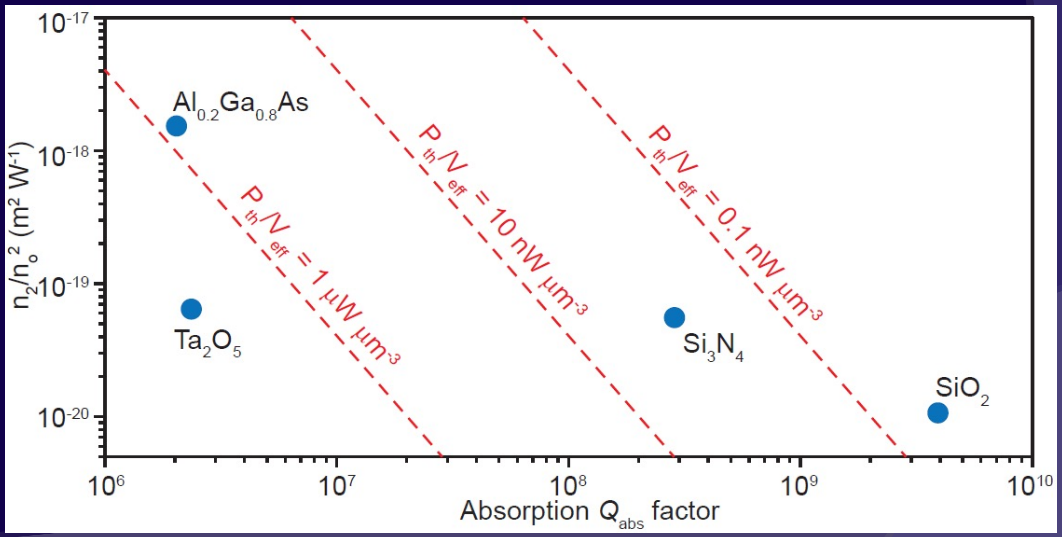
- A revolution in low SWAP functions from existing devices:
  - High resolution spectrometers
  - Ultra-low-noise microwave signal sources
  - High coherence lasers (visible and near IR)
  - Optical gyroscopes
  - Optical clocks
  - Optical frequency synthesizers
  - ..

Q limits of some current photonic materials

Table 1 | Properties of materials in current integrated high-Q microresonators at 1550 nm

Material	Growth method	Structure	n_o	Reported n_2 (10^{-20} m² W⁻¹)	n_2 (10^{-20} m² W⁻¹)	Q_{abs} (M)	σ_{abs} (dB m⁻¹)
SiO_2	Wet oxidation	Amorphous	1.44	2.2	-	3900 ± 200	0.0065 ± 0.0003
Si_3N_4	LPCVD	Amorphous	2.00	24	22 ± 1	290 ± 50	0.12 ± 0.02
$Al_{0.2}Ga_{0.8}As$	MBE	Crystal	3.28	2600	1700 ± 100	2.0 ± 0.2	28 ± 2
Ta_2O_5	IBS	Amorphous	2.06	62	27 ± 3	2.4 ± 0.3	15 ± 2





Gao, Yang, et al, Papp, Bowers, Kippenberg, Vahala arXiv

Opportunities

- A revolution in low SWAP functions from existing devices:
  - High resolution spectrometers
  - Ultra-low-noise microwave signal sources
  - High coherence lasers (visible and near IR)
  - Optical gyroscopes
  - Optical clocks
  - Optical frequency synthesizers
  - ..

- Future possibilities (fiber-like-loss on a chip):
  - FOG and RLG equivalents on chip
  - EDFAs on chip
  - Fiber combs on chip
  - True time delay
  - …

THANK YOU !

www.vahala.caltech.edu