Chip-Based Frequency Combs

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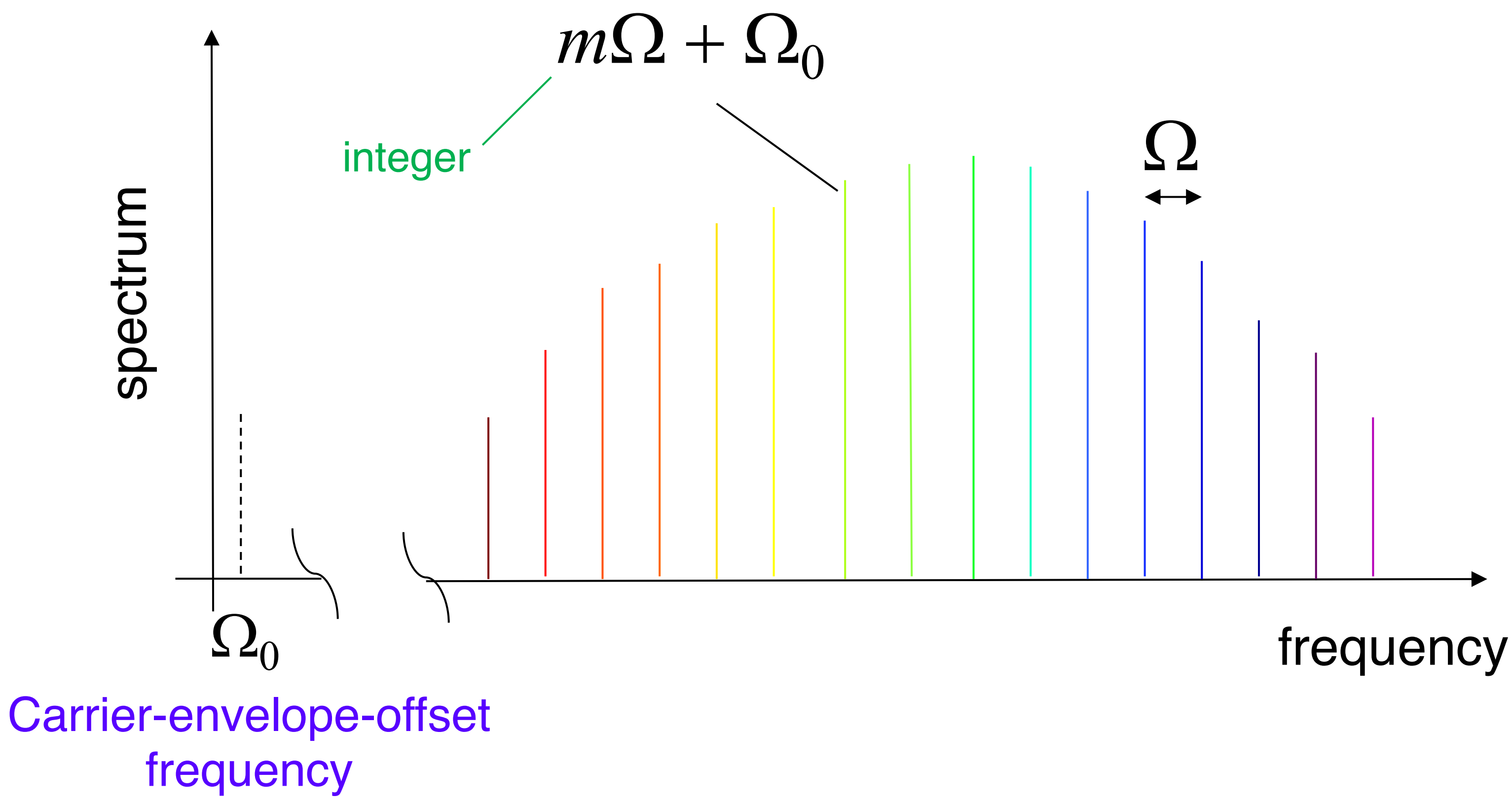
COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

OSA Integrated Photonics Webinar
January 19, 2021

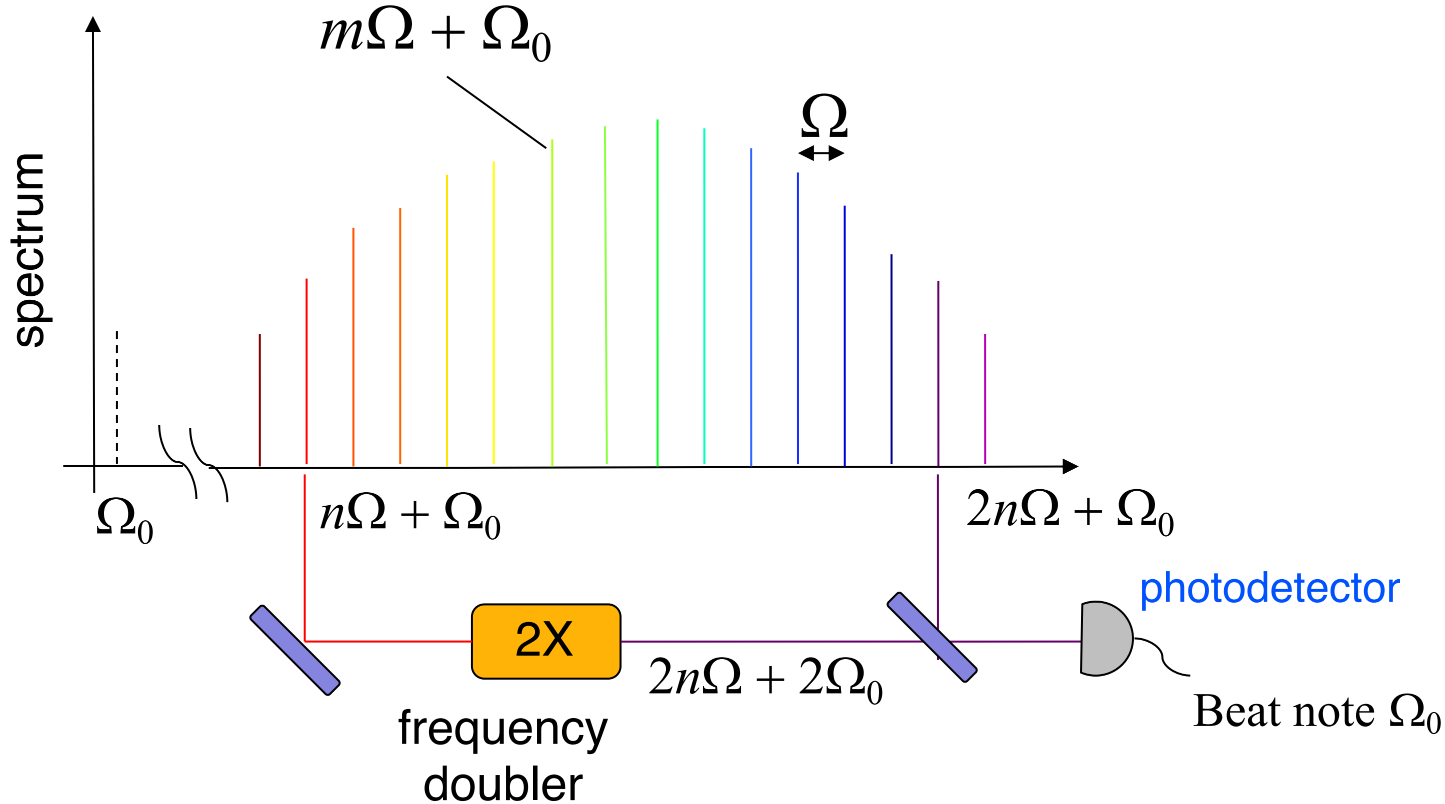
Optical Frequency Combs



- **Direct link between optical and microwave frequencies.**

Telle, et al. Keller, APB (1999); Diddams *et al*., Phys. Rev. Lett. (2000).

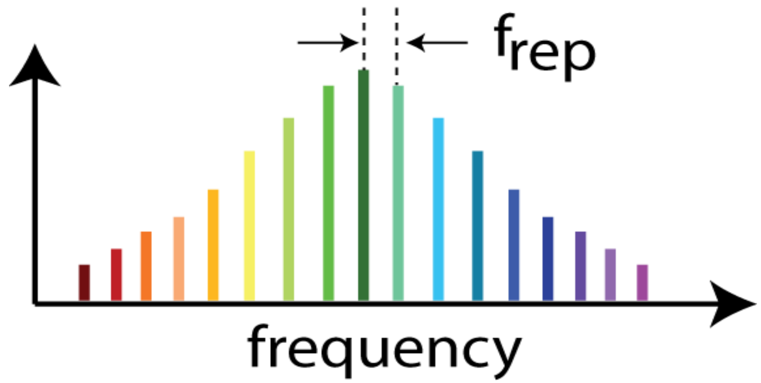
Why an Octave-Spanning Comb?



- Control of the position in the comb frequencies can be achieved.
- Link between microwave & optical frequencies.

Udem et al. (1999); Telle et al. (1999).

Applications of Frequency-Comb Technology



- Chemical/biological sensing
- Optical communications & interconnects
- Optical clockwork
- Astronomical spectral calibration
- Microwave generation
- Navigation (GPS) and distance ranging
- Tests of fundamental laws and constants (*R*, Lamb shift, fine-structure constant)
- Very-long baseline interferometry
- Arbitrary-waveform generation

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Comb Generation with Ultralow Powers and in Highly Miniaturized Devices

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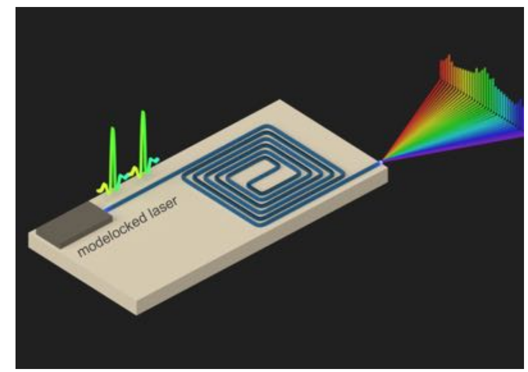
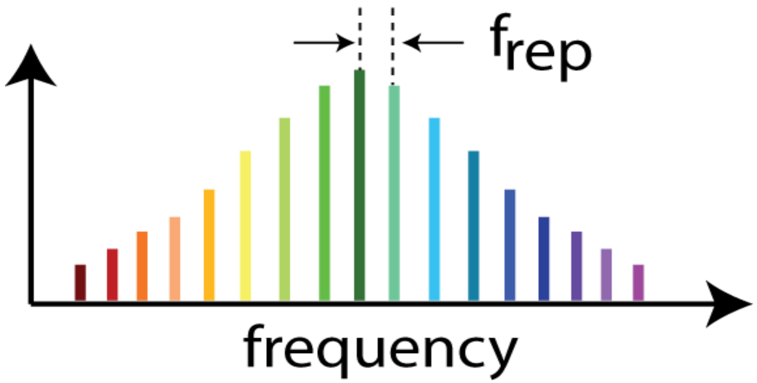
Menlo Systems

centimeter size, < 1 W



- Handheld devices
- WDM sources
- Satellite
- …

Applications of Frequency-Comb Technology



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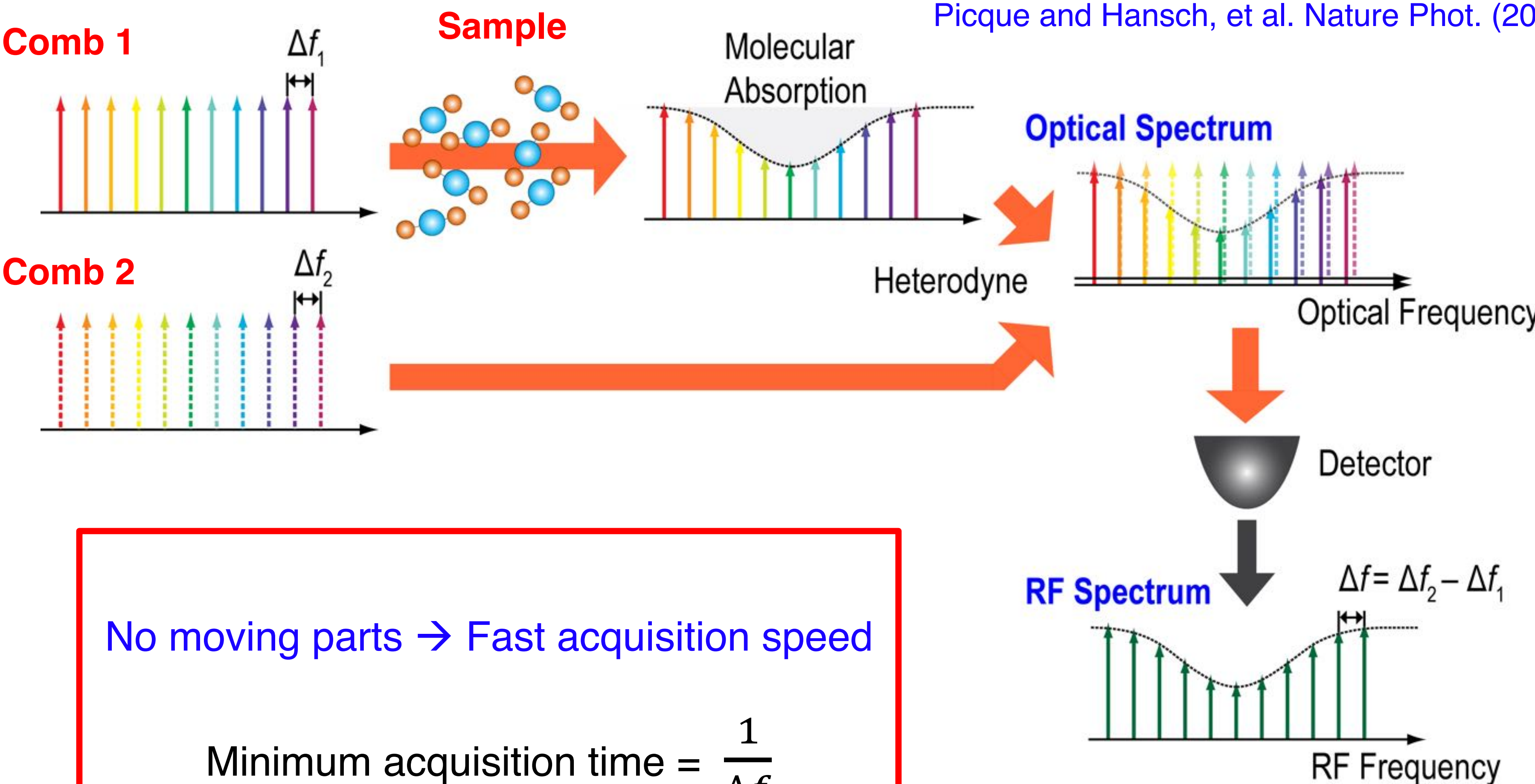
Dual-Comb Spectroscopy

Reviews: Newbury, et al., Optica (2016)
Picque and Hansch, et al. Nature Phot. (2019)



No moving parts → Fast acquisition speed

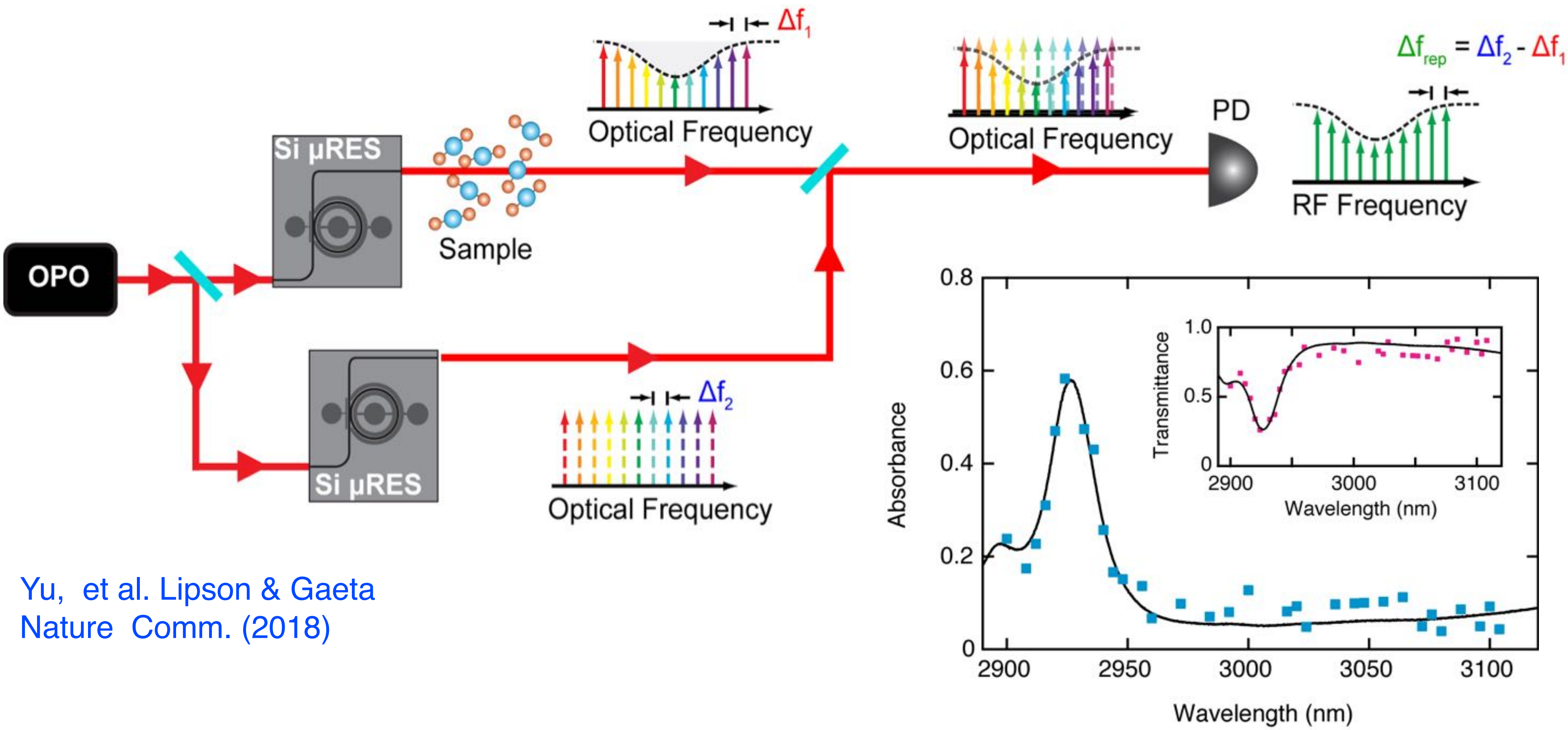
$$\text{Minimum acquisition time} = \frac{1}{\Delta f}$$

Requires only single detector.

Suh, et al. Vahala, Science (2016).
Dutt, et al. Gaeta & Lipson, Science Adv. (2018).
Yu, et al., Lipson & Gaeta, Nature Comm. (2018).

Fast Mid-IR Measurement of Acetone

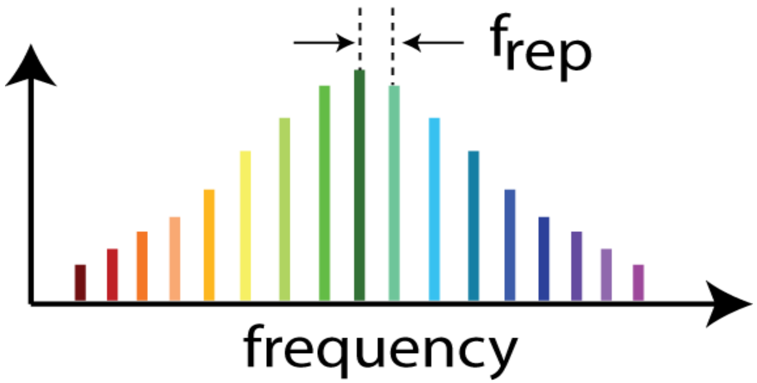
- Measurement of acetone absorption near 2925 nm in 1 μs



Yu, et al. Lipson & Gaeta
Nature Comm. (2018)

Real-time on-chip dual-comb spectrometer for liquid/condensed matter phase studies

Applications of Frequency-Comb Technology



- Chemical/biological sensing
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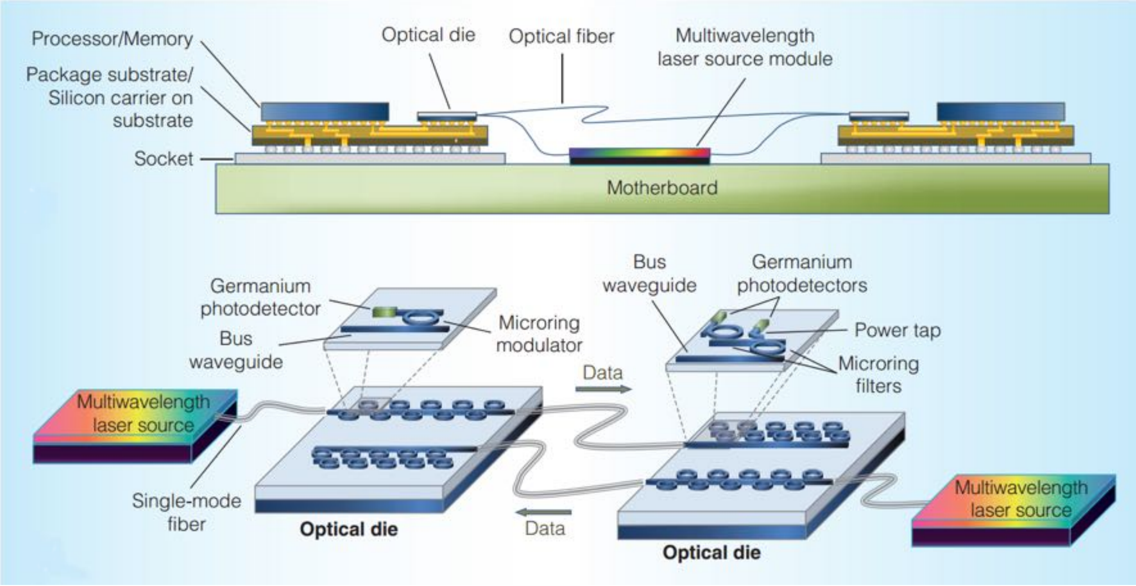
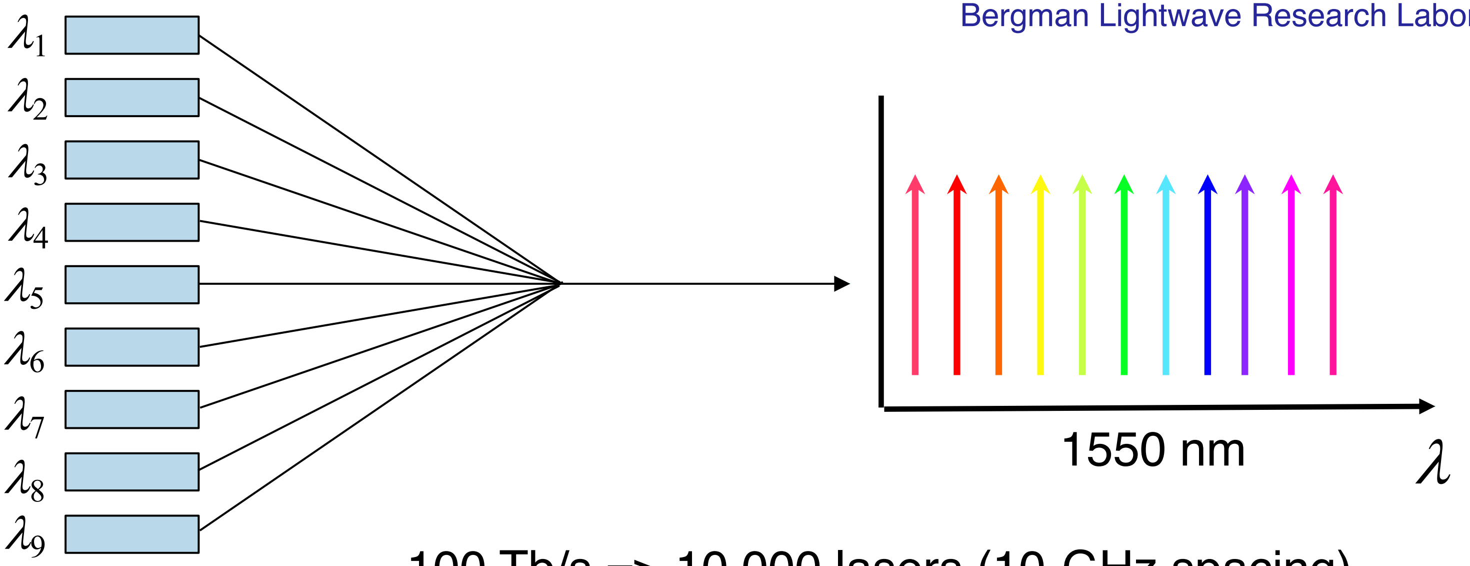
WDM Source for Data Communications



Bergman Lightwave Research Laboratory, Columbia

<u>Multiple Lasers</u>



100 Tb/s => 10,000 lasers (10-GHz spacing)

Chip-Scale Multiple Wavelength Source

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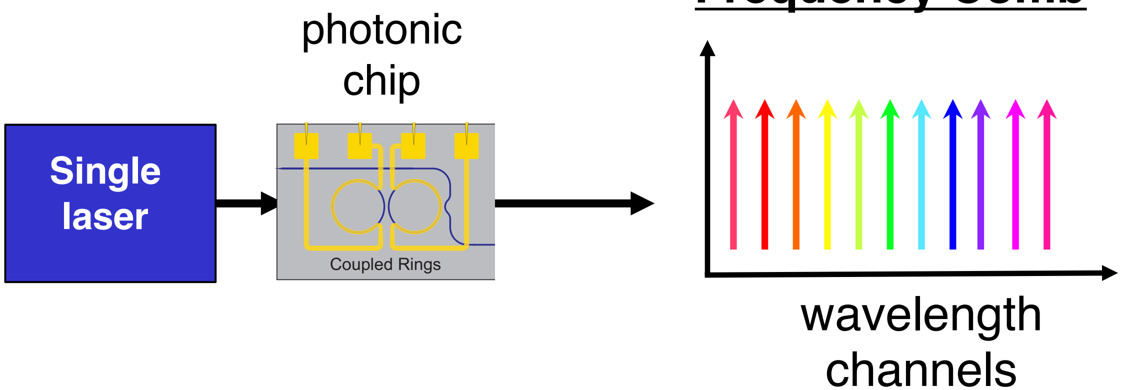
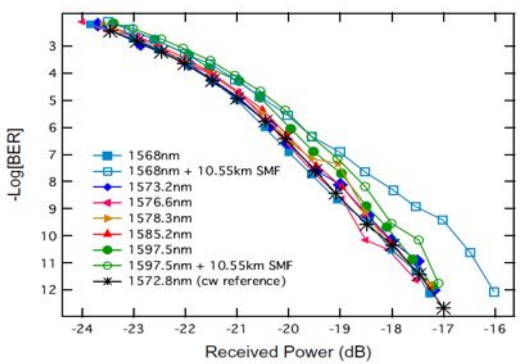
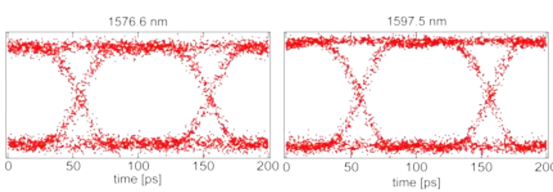
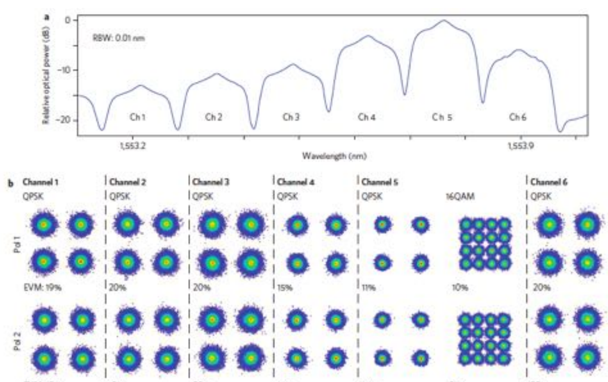
Optical Frequency Comb



Advantages:
i) Cost
ii) Energy efficiency
iii) Scalability and flexibility
iv) Ease of integration

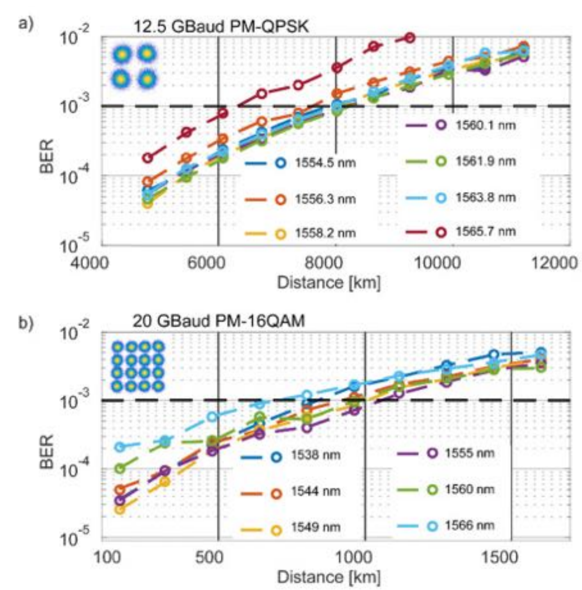






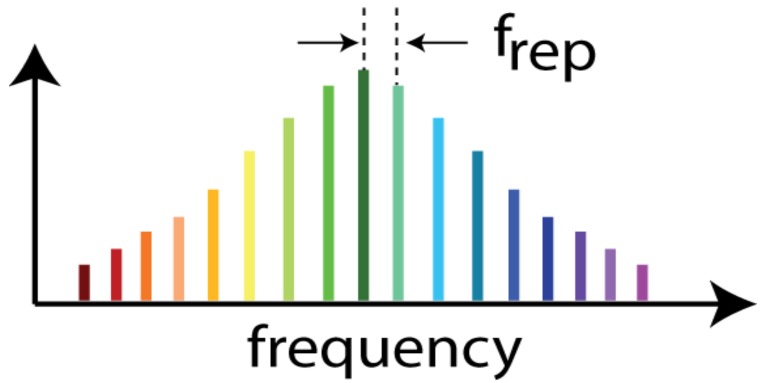
Pfeifle, *et al.*, Nature Photon. (2014).
Marin-Palombo, *et al.*, Nature (2017)

Levy, *et al.*, Gaeta & Lipson Nature Photon. (2010).
Levy, *et al.*, Gaeta & Lipson, PTL (2012).



Fülöp, *et al.*, Opt. Express (2017).
Fülöp, *et al.*, Nature Comm. (2018).

Applications of Frequency-Comb Technology



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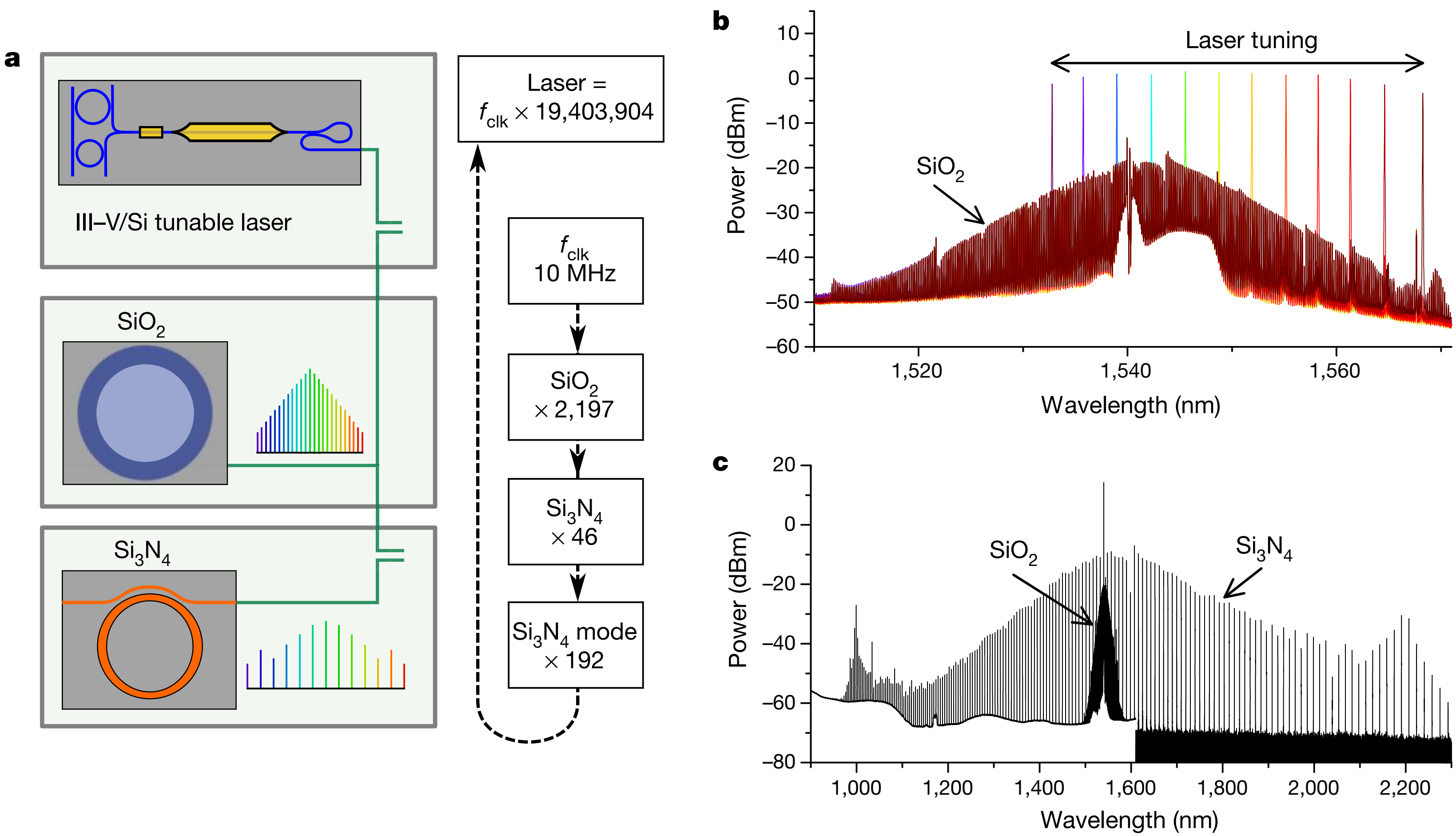
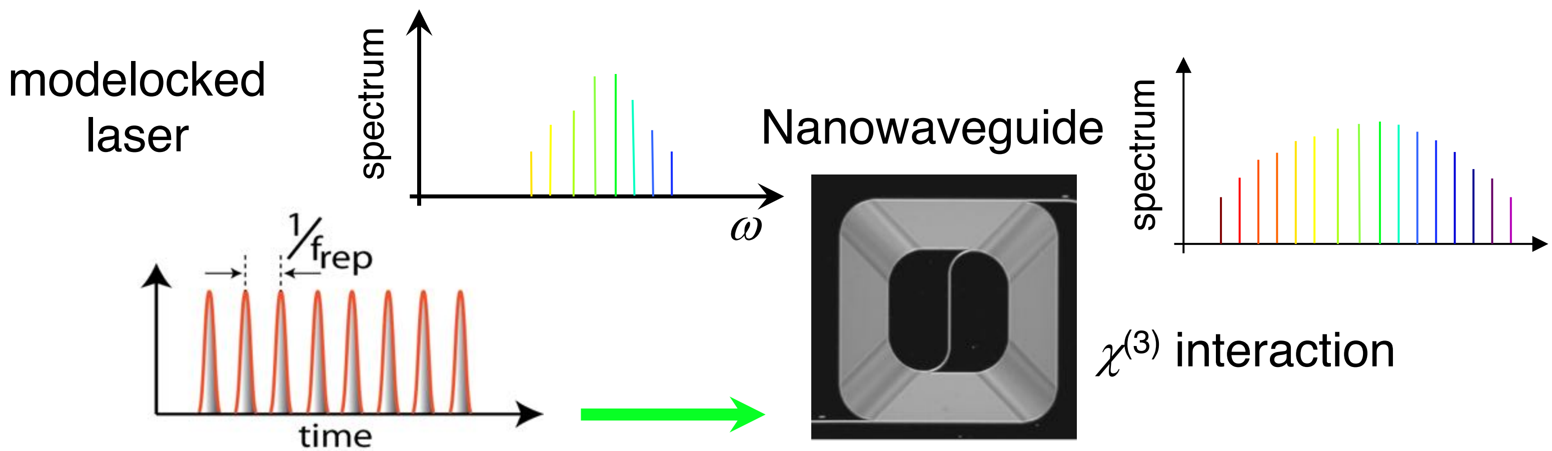
Dual Microcomb Optical Synthesizer

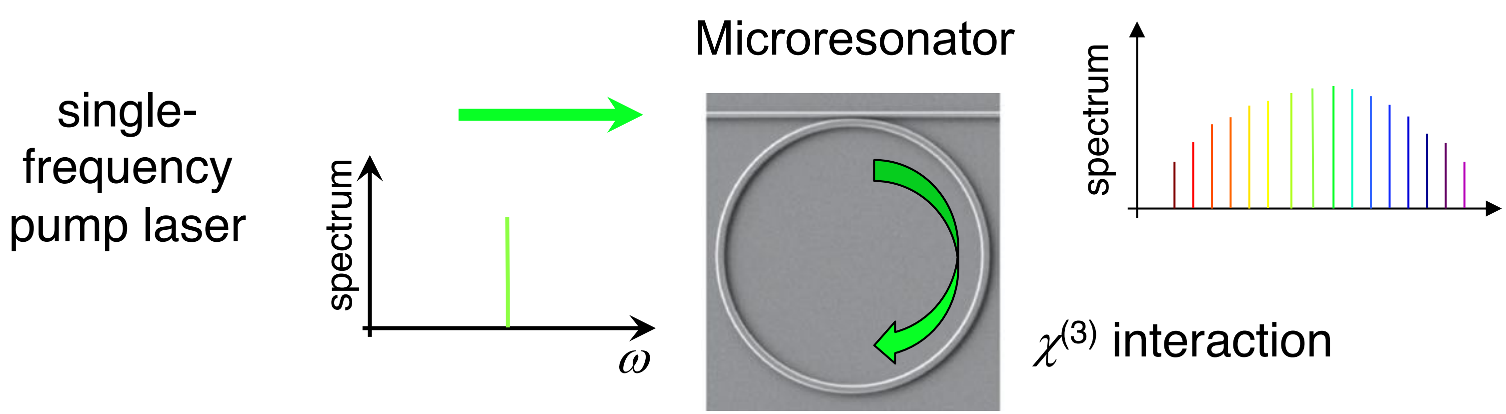
UCSB / NIST / Caltech /EPFL / UVa / Aurrion



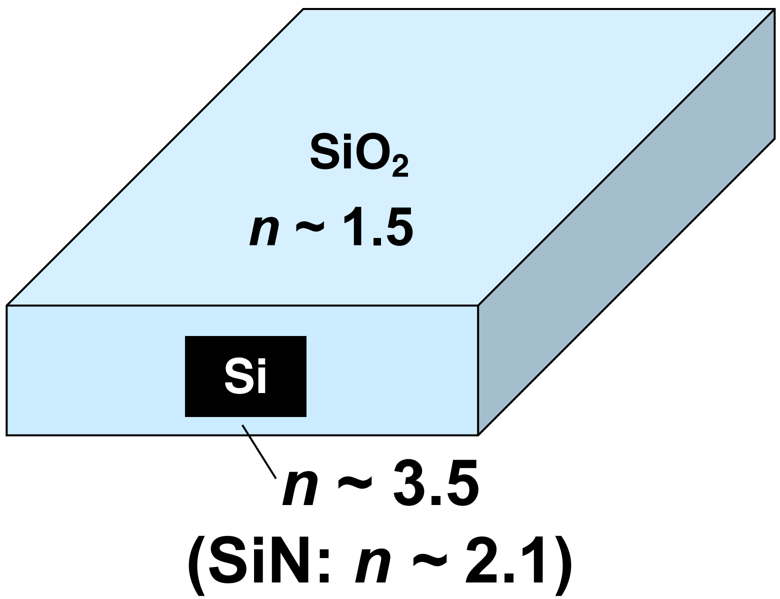
Spencer, et al., Nature (2018)

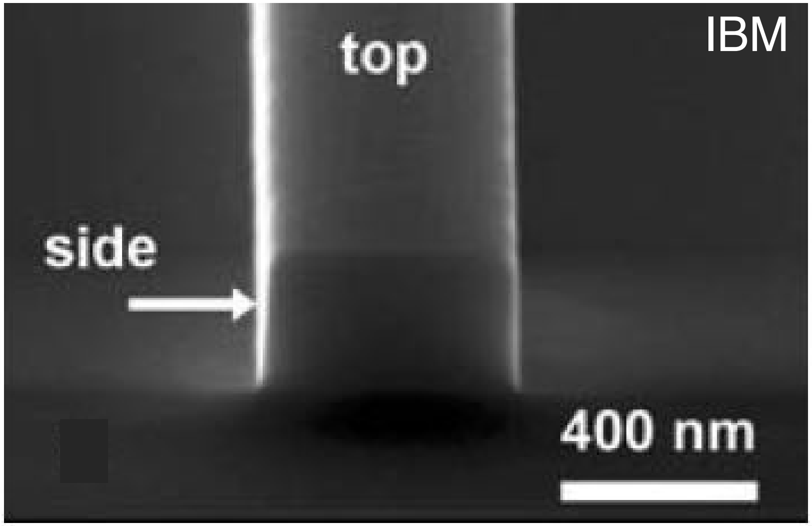
Chip-Based Comb Generation: Cavity Solitons





Nonlinear Optics in Chip-Based Nanowaveguides





Absorption edge: Silicon => ~ 1.1 μm Si_3N_4 => ~ 400 nm

- Nonlinearity of Silicon 100X (Si_3N_4: 10X) silica
- Losses: Silicon – 1 dB/cm (Si_3N_4 – 0.01 dB/cm)
- Light confined to a region < than a wavelength.

Nonlinear Optics in Silicon-Based Nanowaveguides

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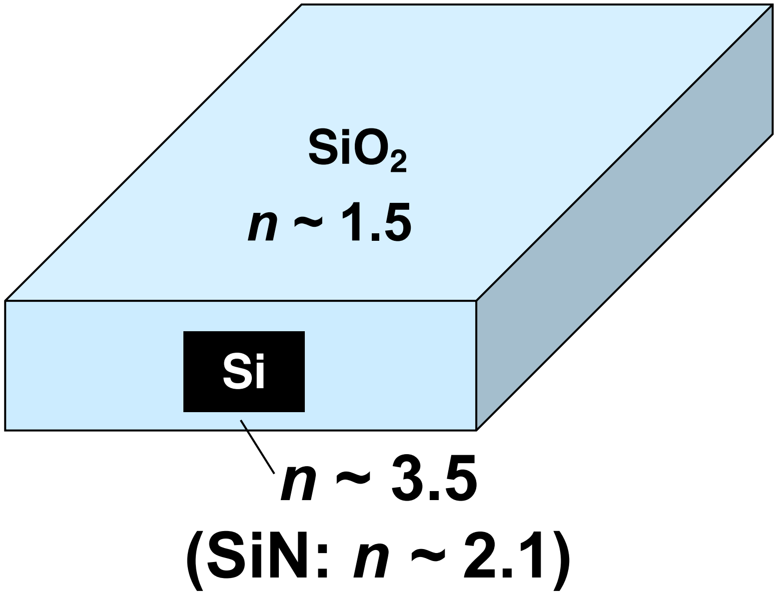
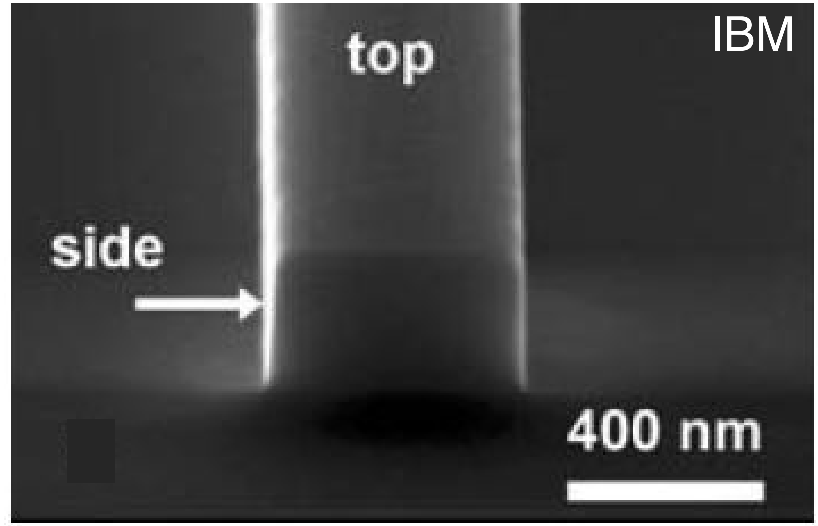
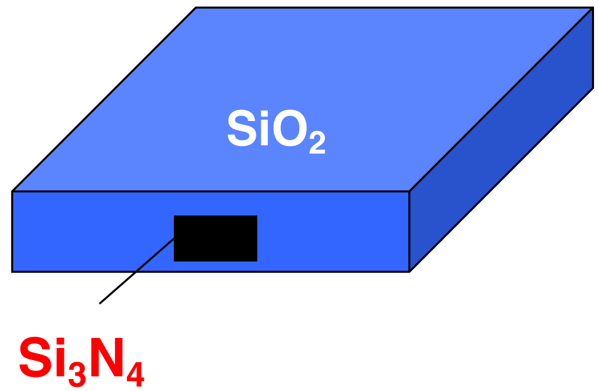


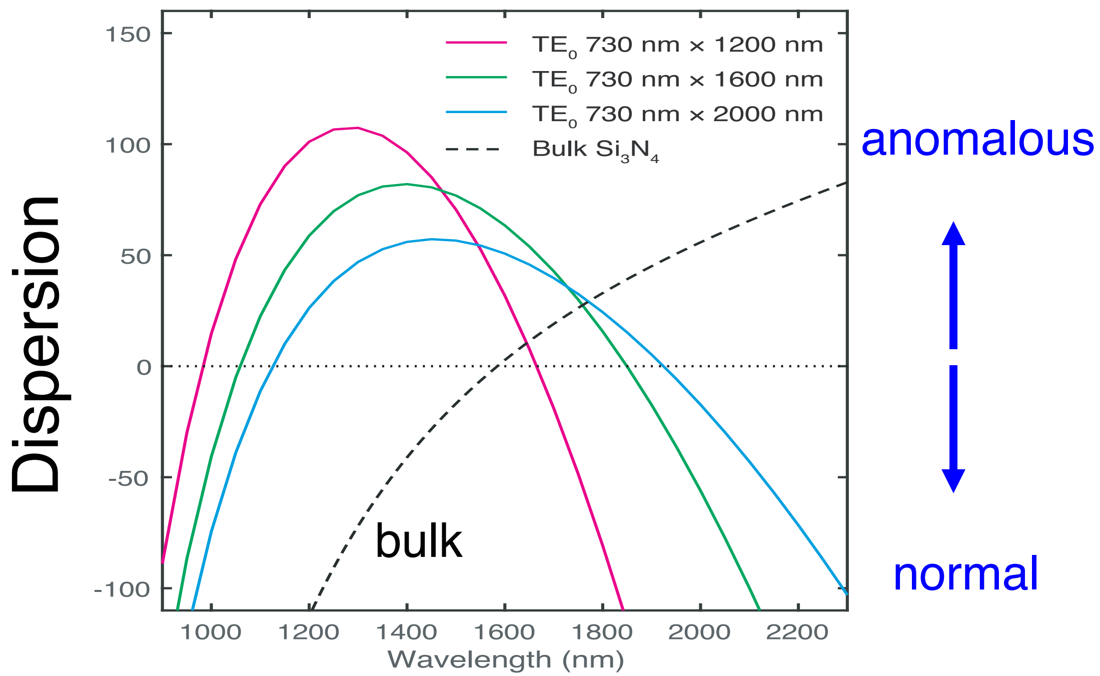


Absorption edge: Silicon => ~ 1.1 *μ*m Si_3N_4 => ~ 400 nm

- Nonlinearity of Silicon 100X (Si_3N_4: 10X) silica
- Losses: Silicon ~ 1 dB/cm (Si_3N_4 – 0.01 dB/cm)
- Light confined to a region < than a wavelength.
- **Dispersion can be engineered.**

Tailoring of GVD in Chip-Based Waveguides





Foster, Turner, Sharping, Schmidt, Lipson, and Gaeta, *Nature* **441**, 960 (2006).
Turner, et al. Gaeta, and Lipson, *Opt. Express* **14**, 4357 (2006).

Chip-Based Comb Generation

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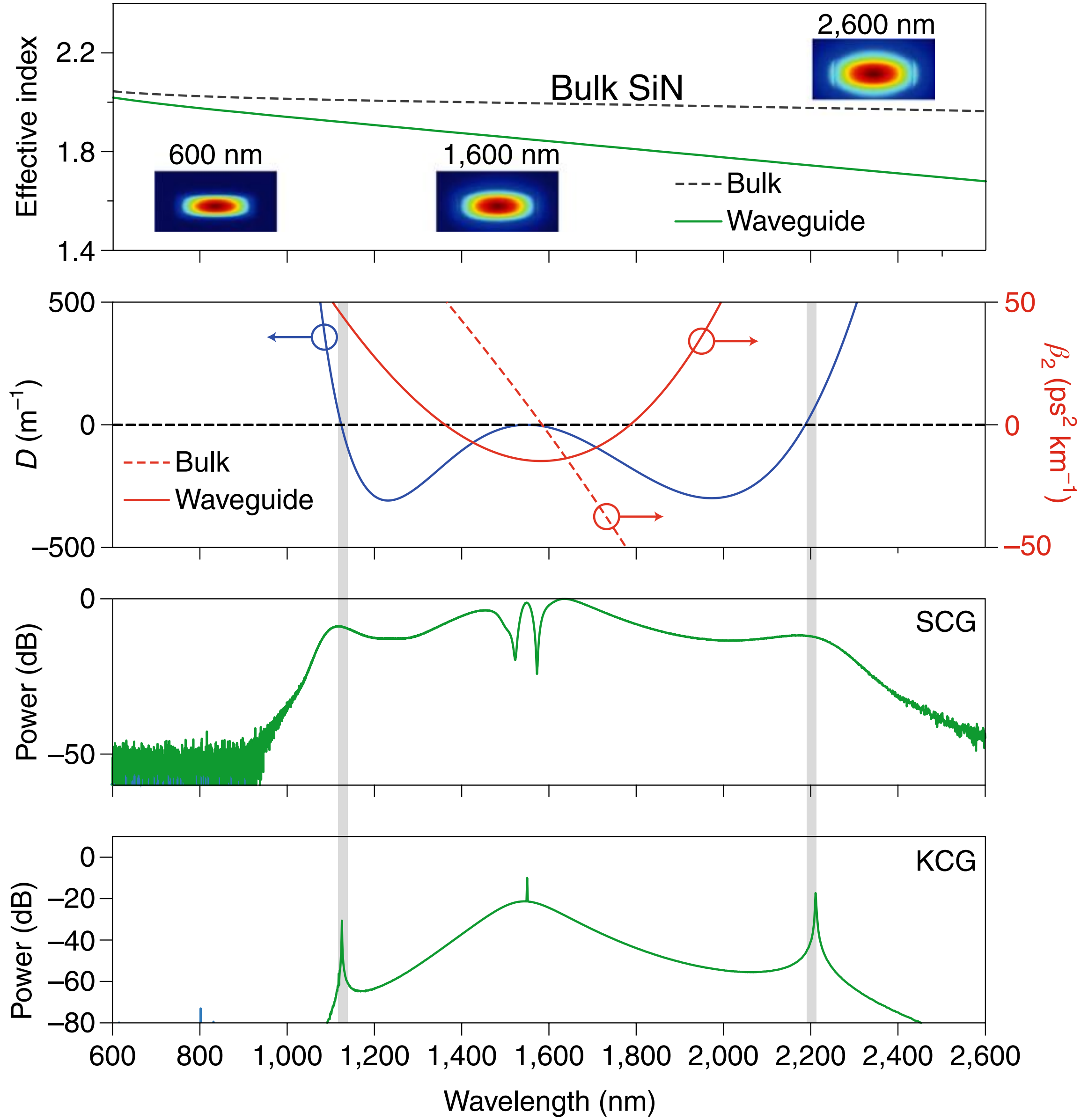
Effective Index

Dispersion

Supercontinuum

Kerr-Comb



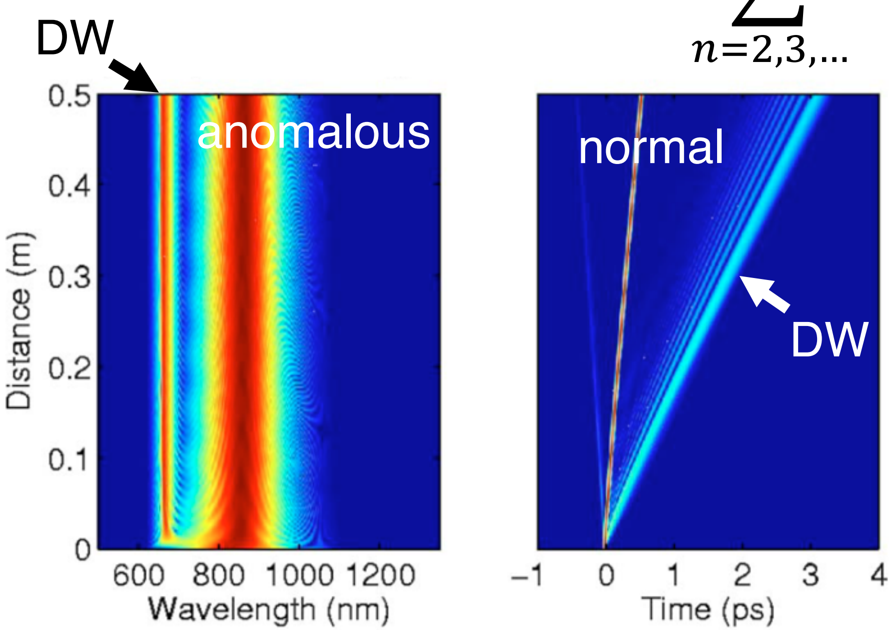
Dispersive Wave (DW) Formation

- Phase matched process that relies on higher-order dispersion
  Dudley *et al*., *Rev. Mod. Phys.* (2006); Efimov, *et al*., PRL (2005).
- Position of DW's given by dispersion operator

dispersion

$$\widehat{D} = \sum_{n=2,3,\ldots} \frac{\beta_n(\omega_0)}{n!}(\omega - \omega_0)^n = 0$$

pump frequency



Energy transfer from soliton (anomalous GVD) to narrowband resonance (normal GVD)

Dudley, *et al*. Rev. Mod. Phys. (2006).

Dispersive Wave Generation in Chip-Based Combs

Effective Index

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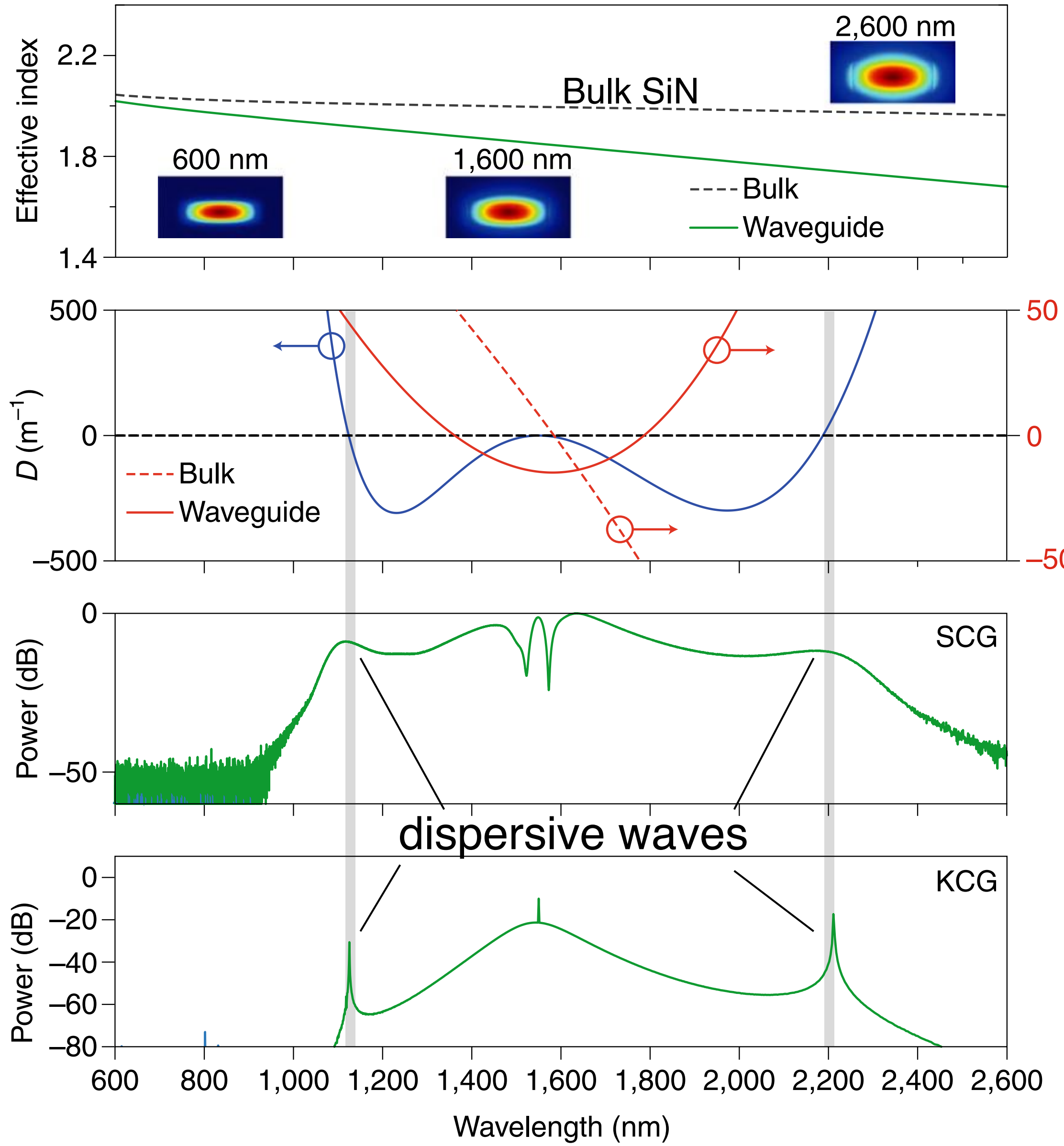
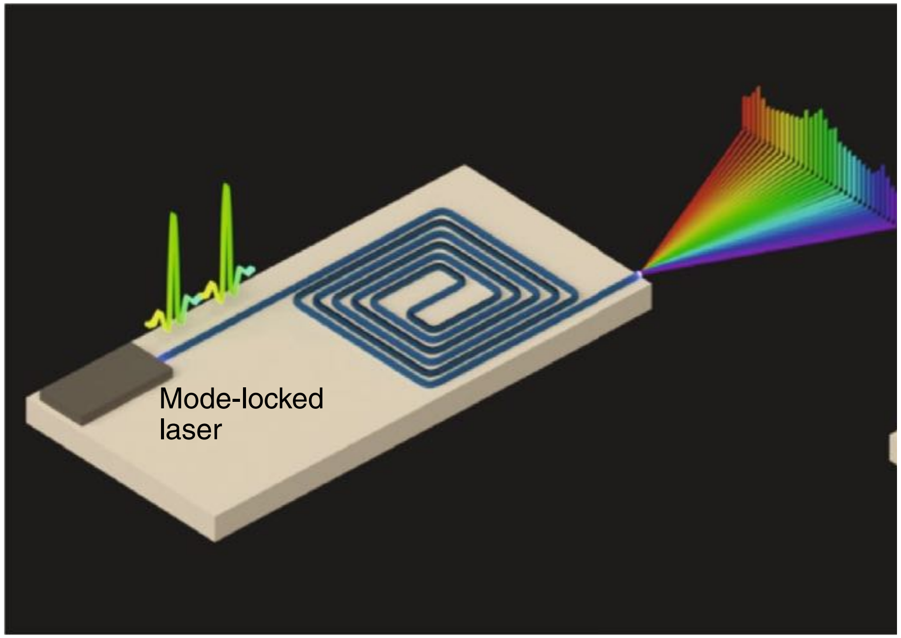
Supercontinuum

Kerr-Comb



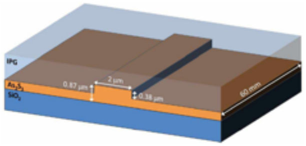
Outline: Chip-Based Comb Generation

Supercontinuum Generation

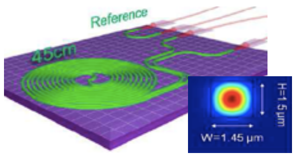


Review Article: Gaeta, Lipson, and Kippenberg, Nature Phot. (2019)

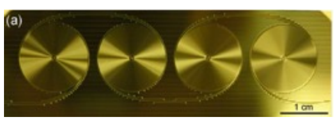
SCG in Integrated Photonic Waveguides



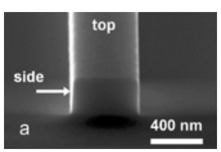
Chalcogenide
Lamont, *et al.*, Opt. Exp. (2008).
Lee, *et al.*, Opt. Lett. (2014).



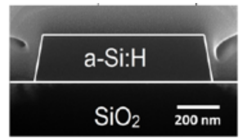
Hydex glass
Duchesne, *et al.*, Opt. Exp. (2010).



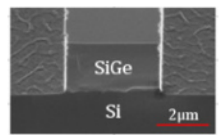
Silica
Oh, *et al.*, Opt. Lett. (2014).



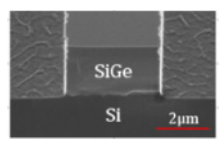
Silicon
Hsieh, *et al.*, Opt. Exp. (2007).
Lau, *et al.*, Opt. Lett. (2014).
F. Leo, *et al.*, Opt. Lett. (2015).
Kuyken, *et al.*, Opt. Exp. (2015).



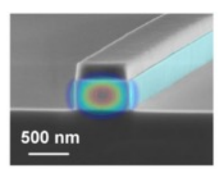
Amorphous silicon
Dave, *et al.*, Opt. Express (2013).
Safioui, *et al.*, Opt. Express (2014).
Leo, *et al.*, Opt. Express (2014).



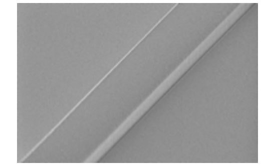
Diamond
Shams-Ansari, *et al.*, Opt. Lett. (2019).



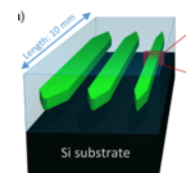
Silicon germanium
Sinobad, *et al.*, Optica (2018).



Aluminum gallium arsenide
Kuyken, *et al.*, Opt. Lett. (2020).



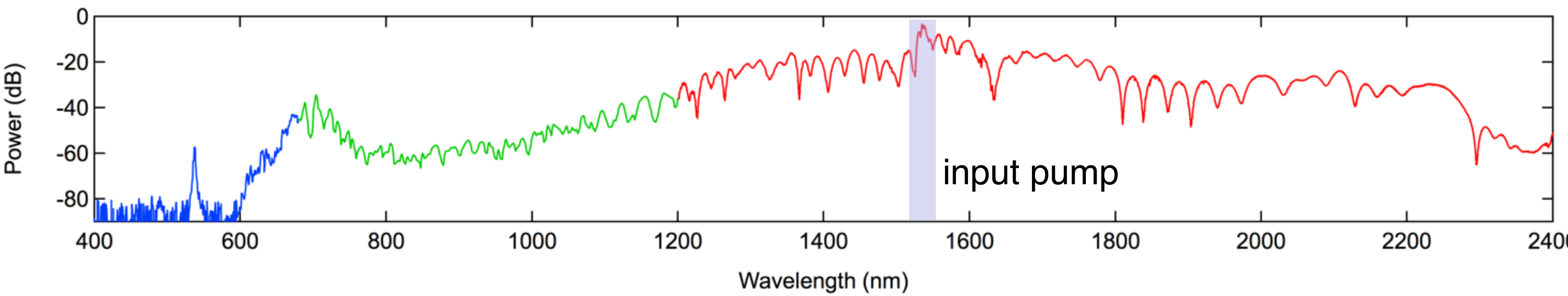
Silicon nitride
Halir, *et al.*, Opt. Lett. (2012).
Chavez Boggio, *et al.*, JOSA B (2014).
Wang, *et al.*, LPR (2015).
Liu, *et al.*, Opt. Lett. (2016).
Carlson, *et al.*, Opt. Lett. (2017).
Porcel, *et al.*, Opt. Exp. (2017).
Guo, *et al.*, Nature Photon. (2018).



Aluminum nitride
Hickstein, *et al.*, P.R. Appl. (2017).

Lithium niobate
Yu, *et al.*, Opt. Lett. (2019).
Lu, *et al.*, Opt. Lett. (2019).
Jankowski, *et al.*, Optica (2020).

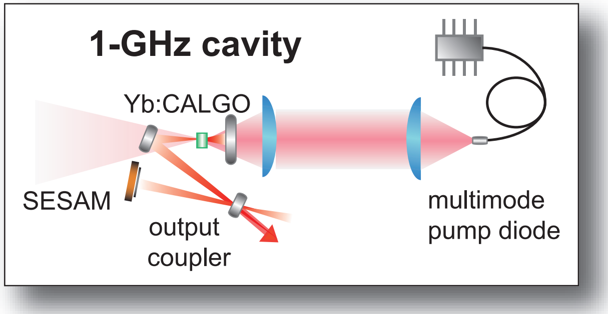
Si_3N_4 - Flexibility in Operation Wavelength



- 5-cm Si_3N_4 waveguide, 730 × 1500 nm cross section
- 1560 nm pump, 100-fs pulse duration, 10 mW coupled power (80 MHZ)
- > 2 octave spanning comb
- Wide transparency (400 – 4600 nm) visible to mid-IR

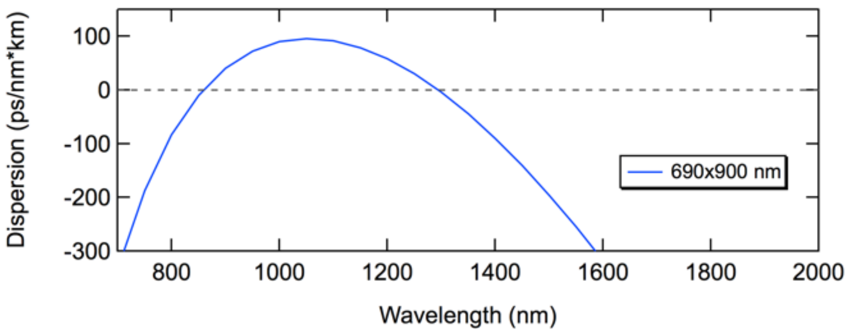
Coherence Characterization of Supercontinuum Spectrum (Experiment)

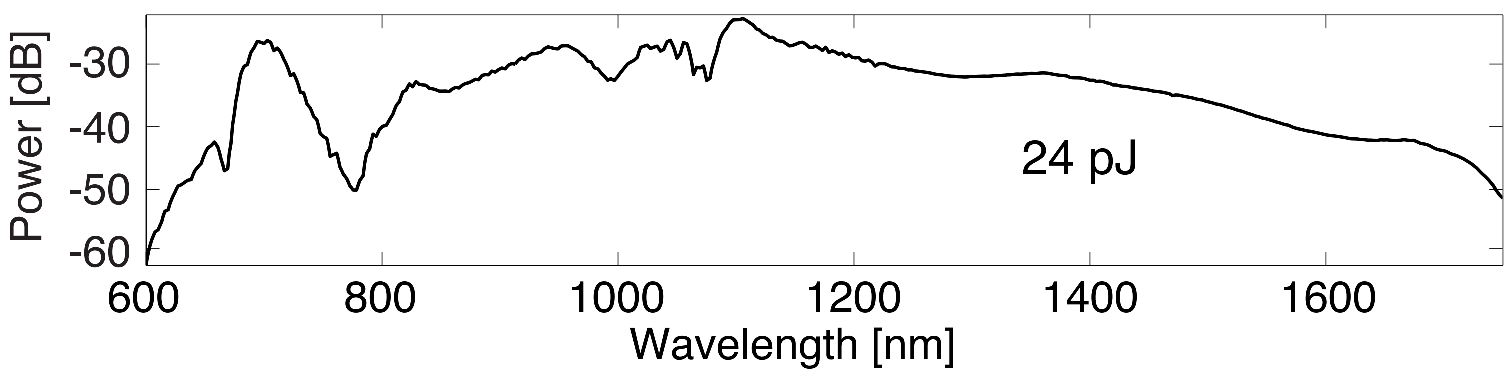
- Collaboration with **Keller Group** (ETH Zürich)



- Pump with 100-fs, 1-GHz repetition rate, 1055 nm
  [A. Klenner *et al.*, Opt. Express (2014).]

- 7.5 mm Si_3N_4 waveguide, 690 × 900 nm



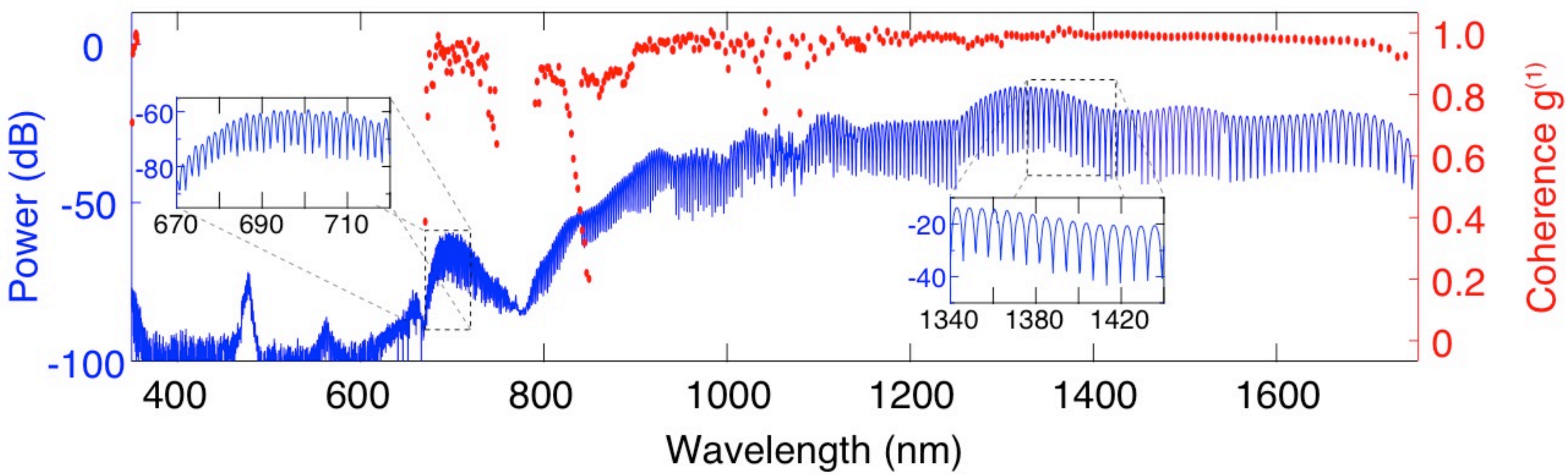


Johnson, et al. Keller, Lipson, & Gaeta, Opt. Lett. (2015);

Coherence of SCG

- Measure fringes in asymmetric Michelson interferometer
  [F. Lu *et al.*, Opt. Express (2004).]
- Extract visibility and coherence
  [J W. Nicholson *et al.*, Opt. Express (2004); X. Gu *et al.*, Opt. Express (2003)]

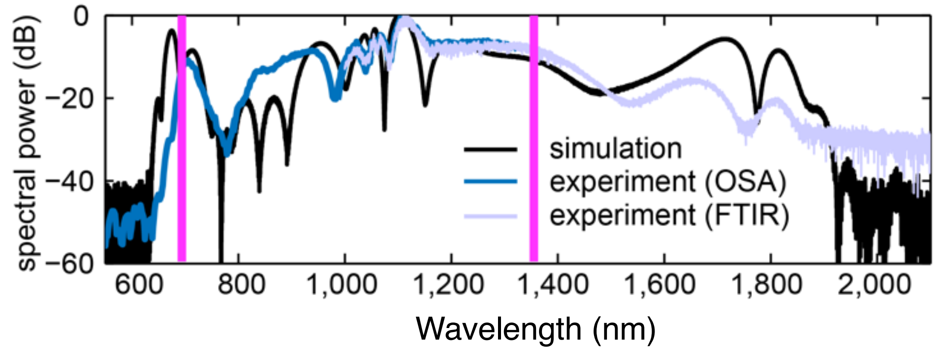
$$V(\lambda) = \frac{I_{max}(\lambda) - I_{min}(\lambda)}{I_{max}(\lambda) + I_{min}(\lambda)} \qquad \left|g_{12}^{(1)}(\lambda)\right| = \frac{V(\lambda)\left[I_1(\lambda) + I_2(\lambda)\right]}{2\left[I_1(\lambda) I_2(\lambda)\right]^{1/2}}$$

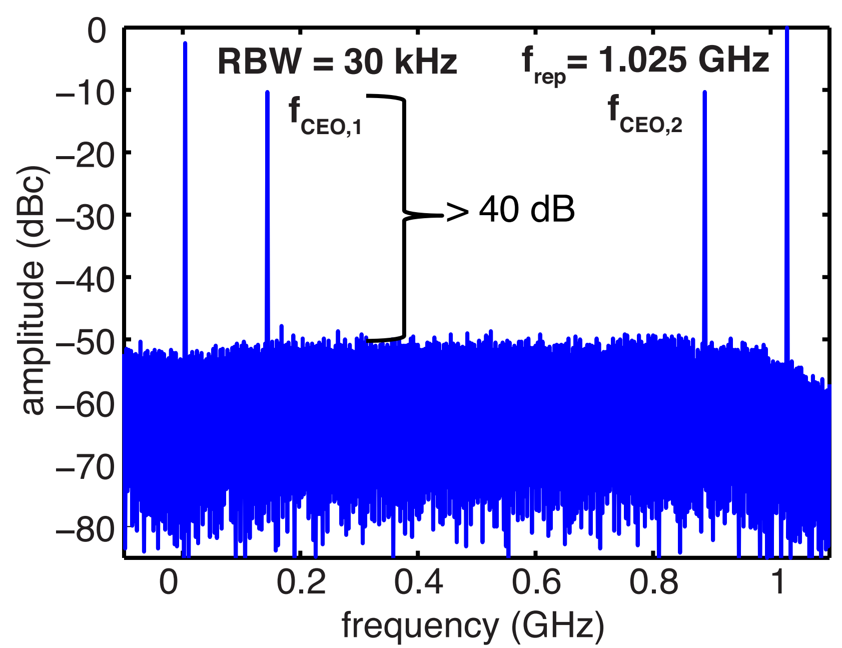


Johnson, et al., Lipson & Gaeta, Opt. Lett. (2015).

Comb-Offset Detection and Stabilization Using SCG in Si_3N_4

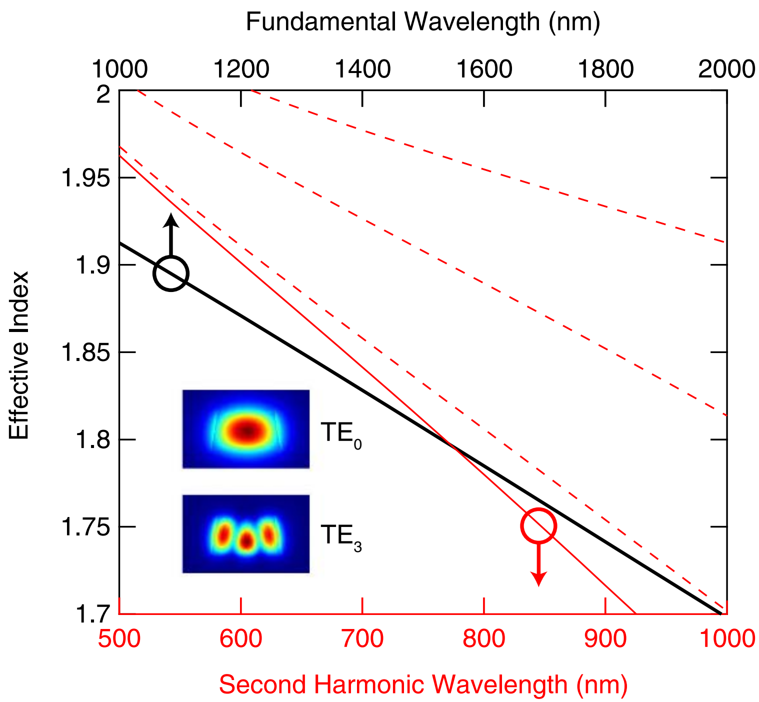
- Carrier envelop offset frequency (f_{ceo}) beatnote from *f*-to-2*f* interferometry
- Coupled pulse energy = 36 pJ
  Peak power = 0.34 kW
- f_{ceo} signal-to-noise ratio 40 dB

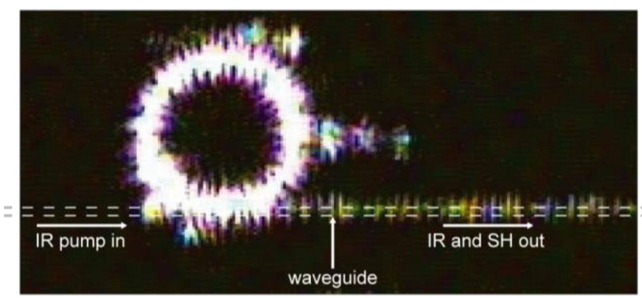




Mayer, et al., Lipson, Gaeta, Keller, Opt. Express (2015).

Simultaneous SHG and SCG with Si_3N_4





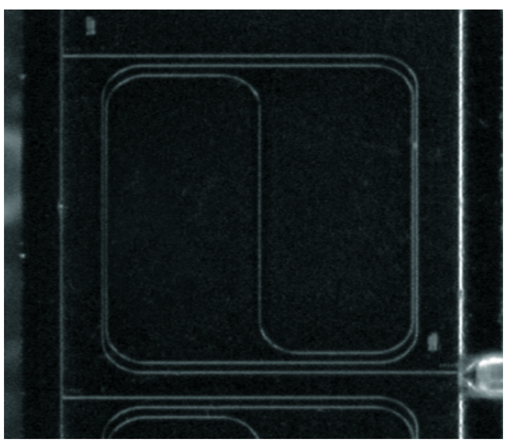
Levy, et al. Gaeta & Lipson, Opt. Express (2011).

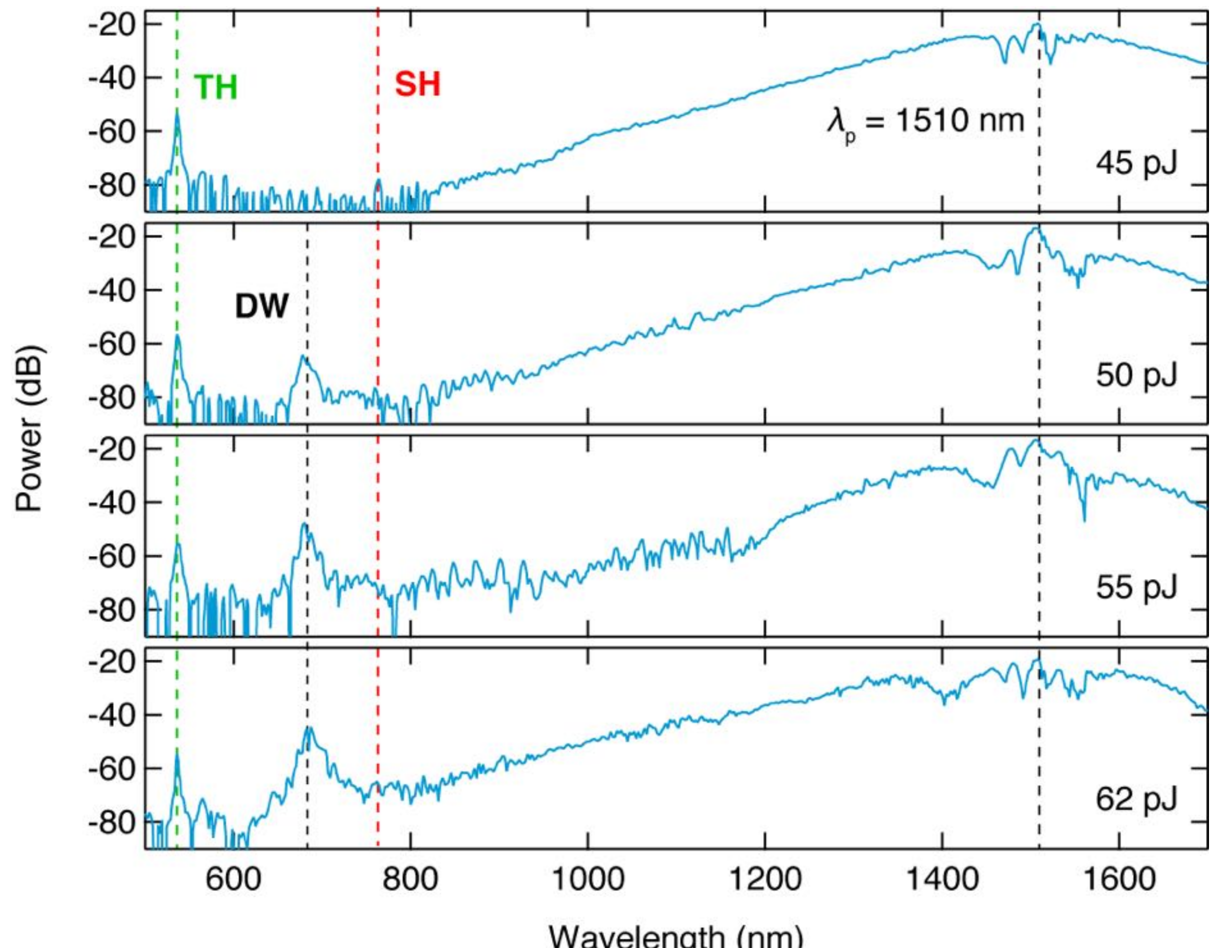
f_{CEO} Detection via Simultaneous SCG and SHG

- Si_3N_4 can exhibit $\chi^{(2)}$ response due to symmetry breaking at waveguide interface, high film stress, or electromigration

  Lettieri, et al. (2002); Levy, et al. (2011); Khurgin, et al. (2015); Billat et al. (2017).

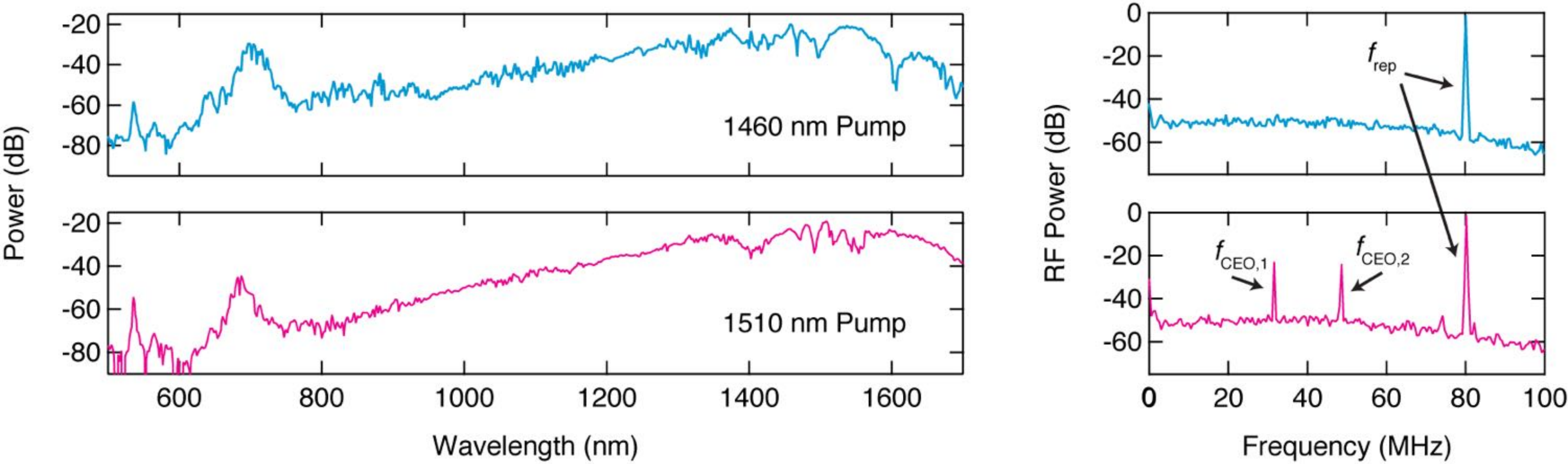
- 2-cm-long Si_3N_4 waveguide
- 200-fs pulse





Okawachi, et al., Lipson & Gaeta, Opt. Lett. (2018).

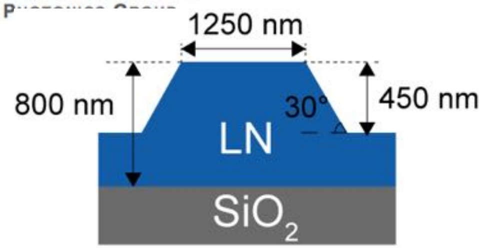
f_{CEO} Detection via Simultaneous SCG and SHG

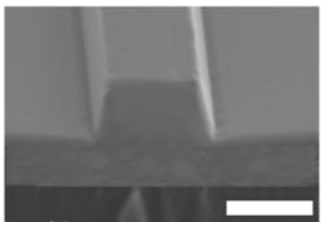


- Measured f_{CEO} beatnote with 27 dB signal-to-noise ratio.
- Carrier envelope offset frequency detection in a single device!

Okawachi, et al., Lipson & Gaeta, Opt. Lett. (2018).

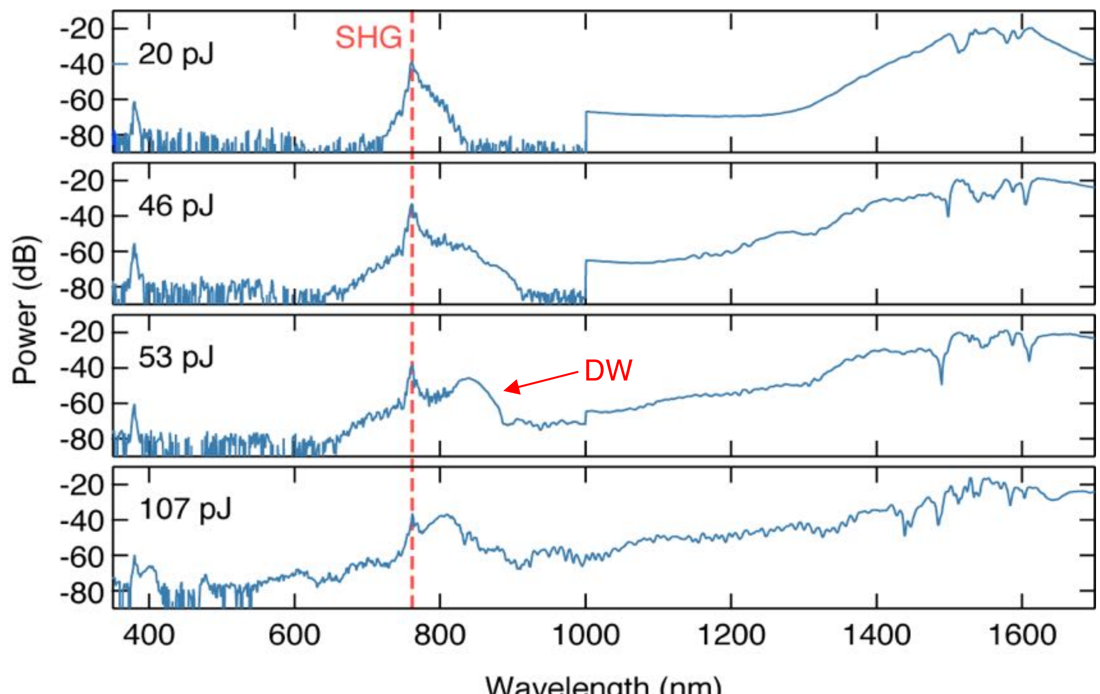
Lithium Niobate (LN) for SCG and SHG



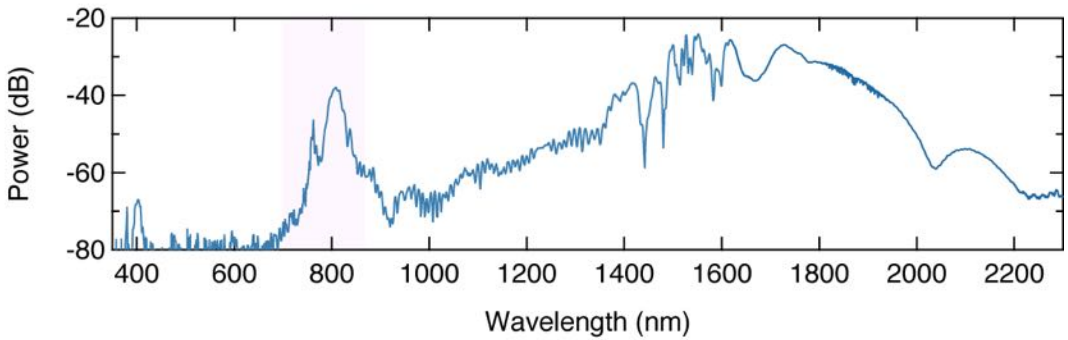


Devices fabricated by Loncar Group

- Modelocked 90-fs pulses at 1560 nm
- 5-mm-long LN waveguide
- TE mode to access largest $\chi^{(2)}$ nonlinear tensor component



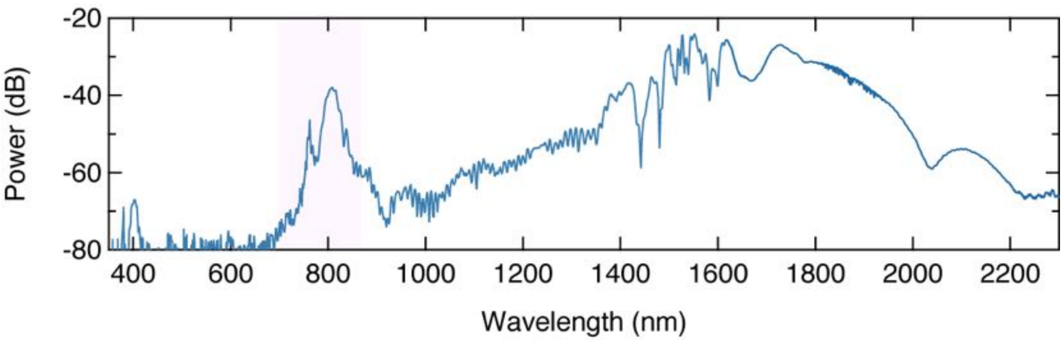
On-Chip f-2f Interferometry for f_{CEO} Stabilization

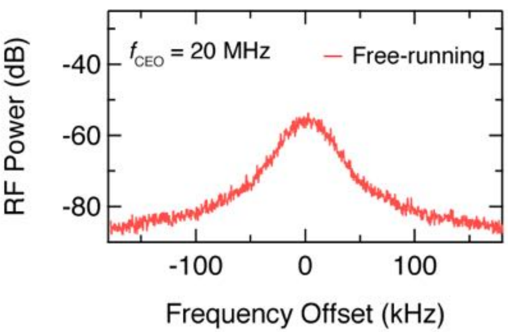


- Octave-spanning spectrum (700 – 2200 nm) with 107 pJ pulse energy

- Direct detection of f_{CEO} with silicon avalanche photodiode (400 – 1000 nm wavelength range)

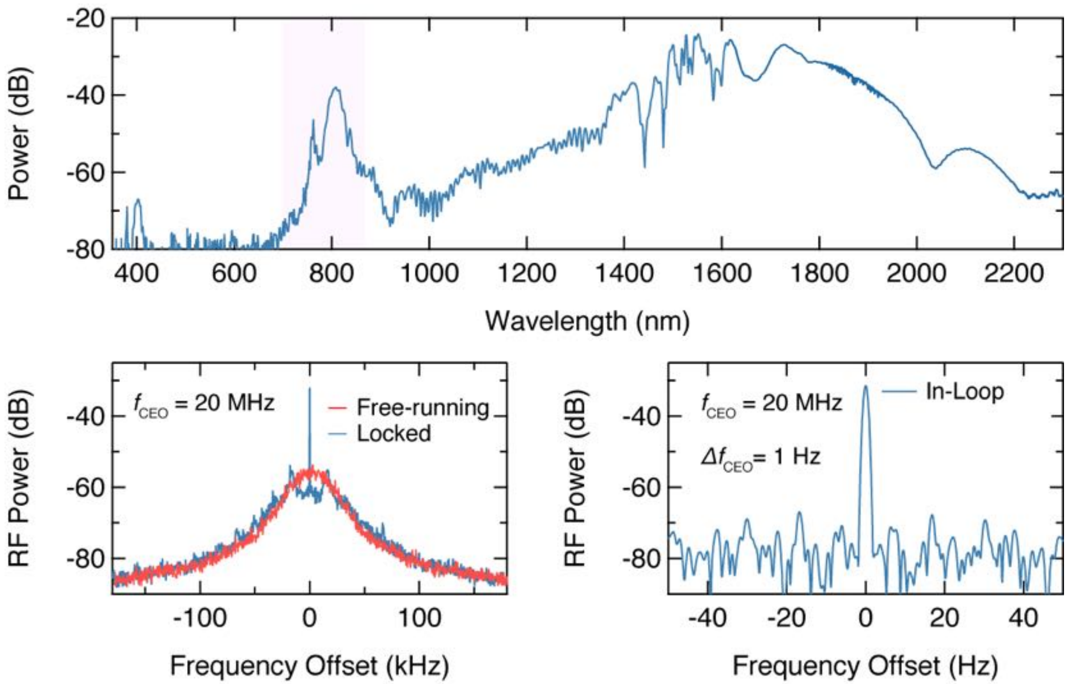
On-Chip f-2f Interferometry for f_{CEO} Stabilization





- f_{CEO} phase locked to rubidium frequency standard
- Feedback loop with phase detector and PID controller

On-Chip f-2f Interferometry for f_{CEO} Stabilization



- f_{CEO} has 3-dB bandwidth of 1 Hz (resolution limited)

On-Chip f-2f Interferometry for f_{CEO} Stabilization

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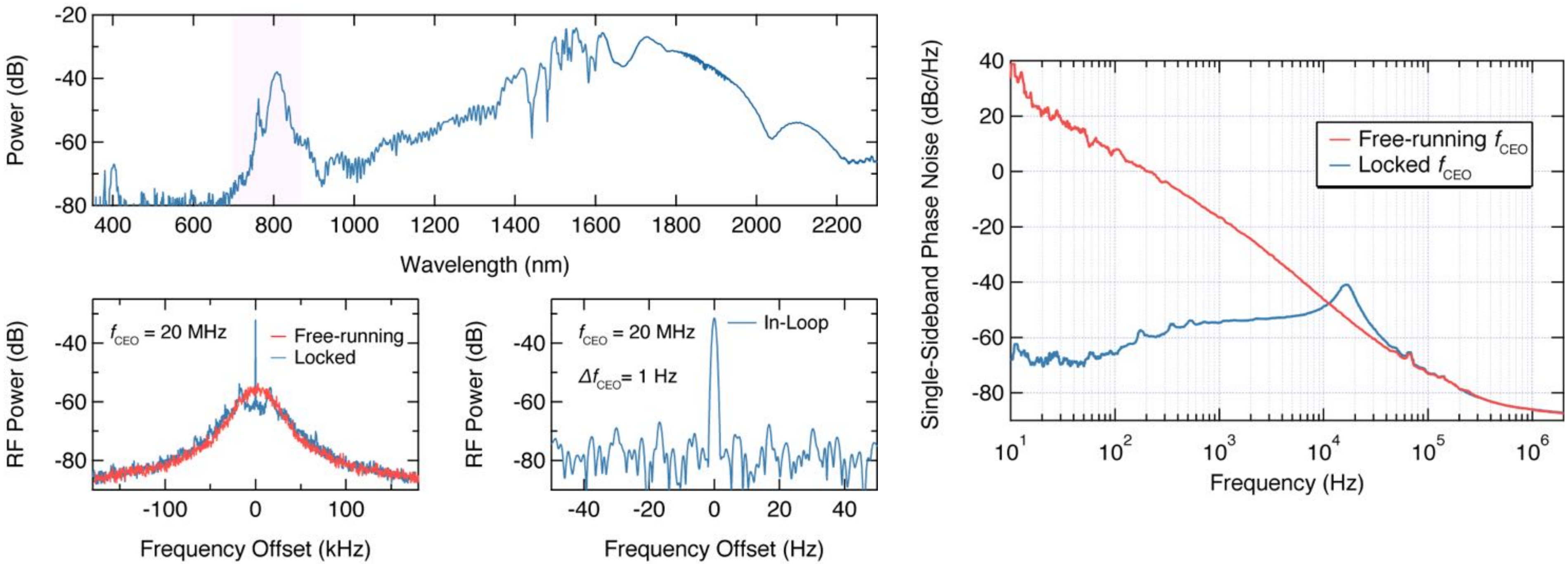
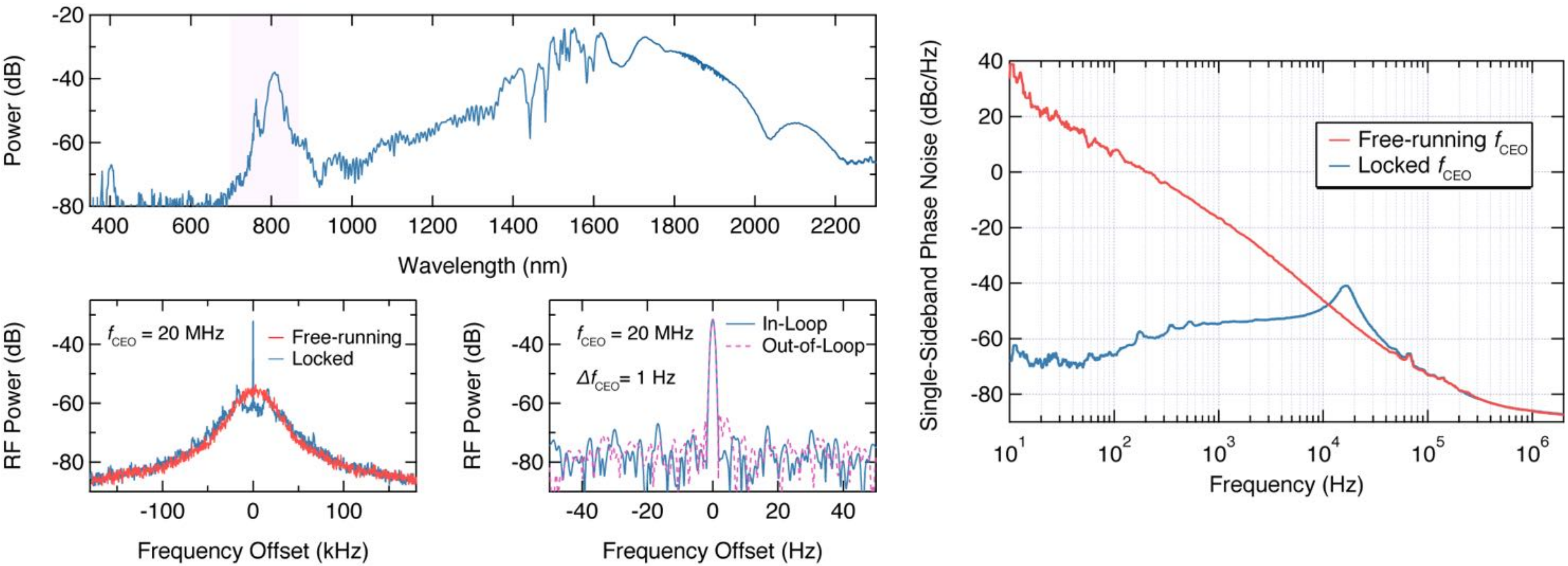


- f_{CEO} has 3-dB bandwidth of 1 Hz (resolution limited)
- >100 dB/Hz reduction of phase noise at 10 Hz

Okawachi, *et al. Optica* (2020).

On-Chip f-2f Interferometry for f_{CEO} Stabilization

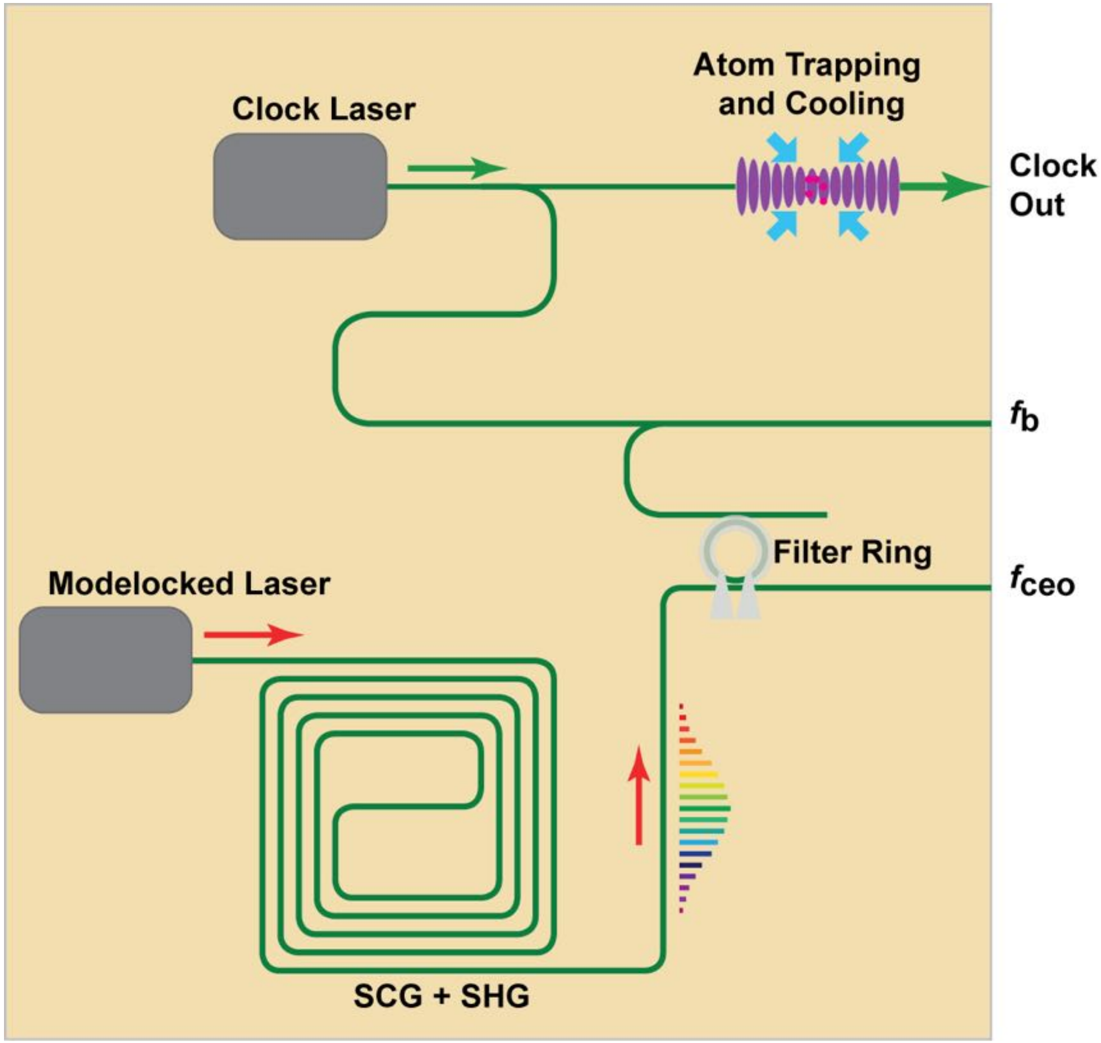


- f_{CEO} has 3-dB bandwidth of 1 Hz (resolution limited)
- >100 dB/Hz reduction of phase noise at 10 Hz
- Out-of-loop f_{CEO} measurement using conventional *f*-2*f* interferometer

Okawachi, *et al. Optica* (2020).

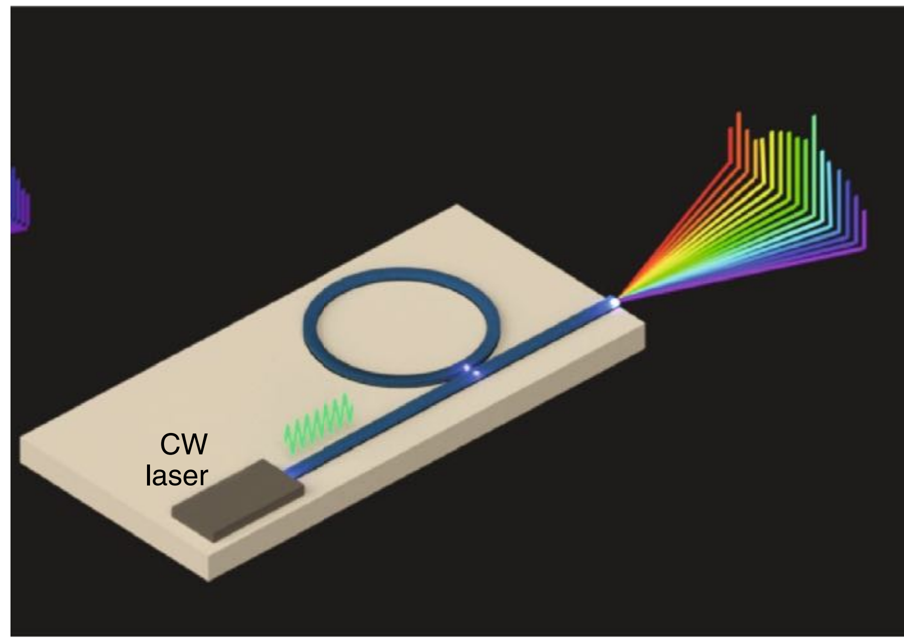
Future: Fully integrated Devices

All-Optical Clock



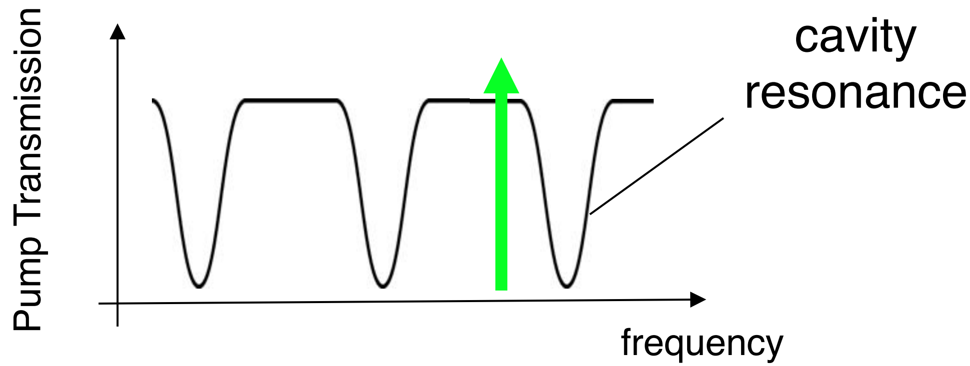
Outline: Chip-Based Comb Generation

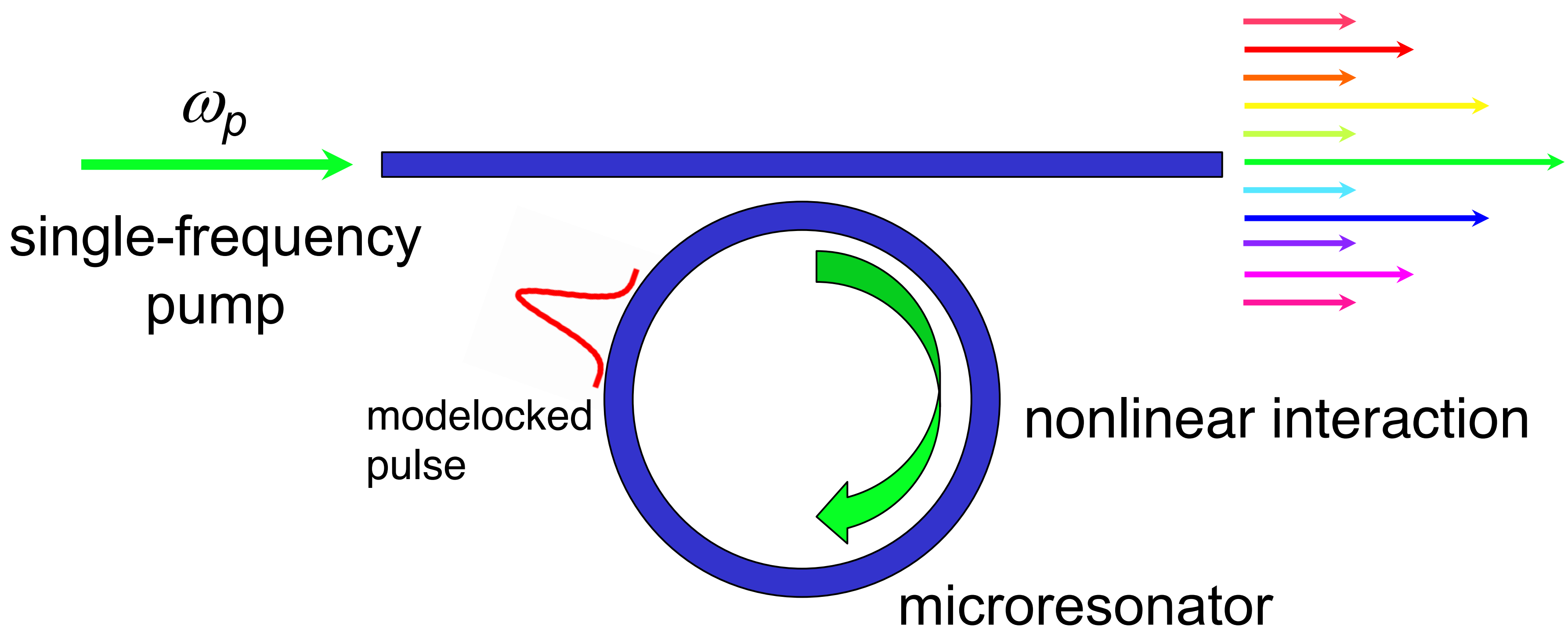
Kerr-Comb Generation



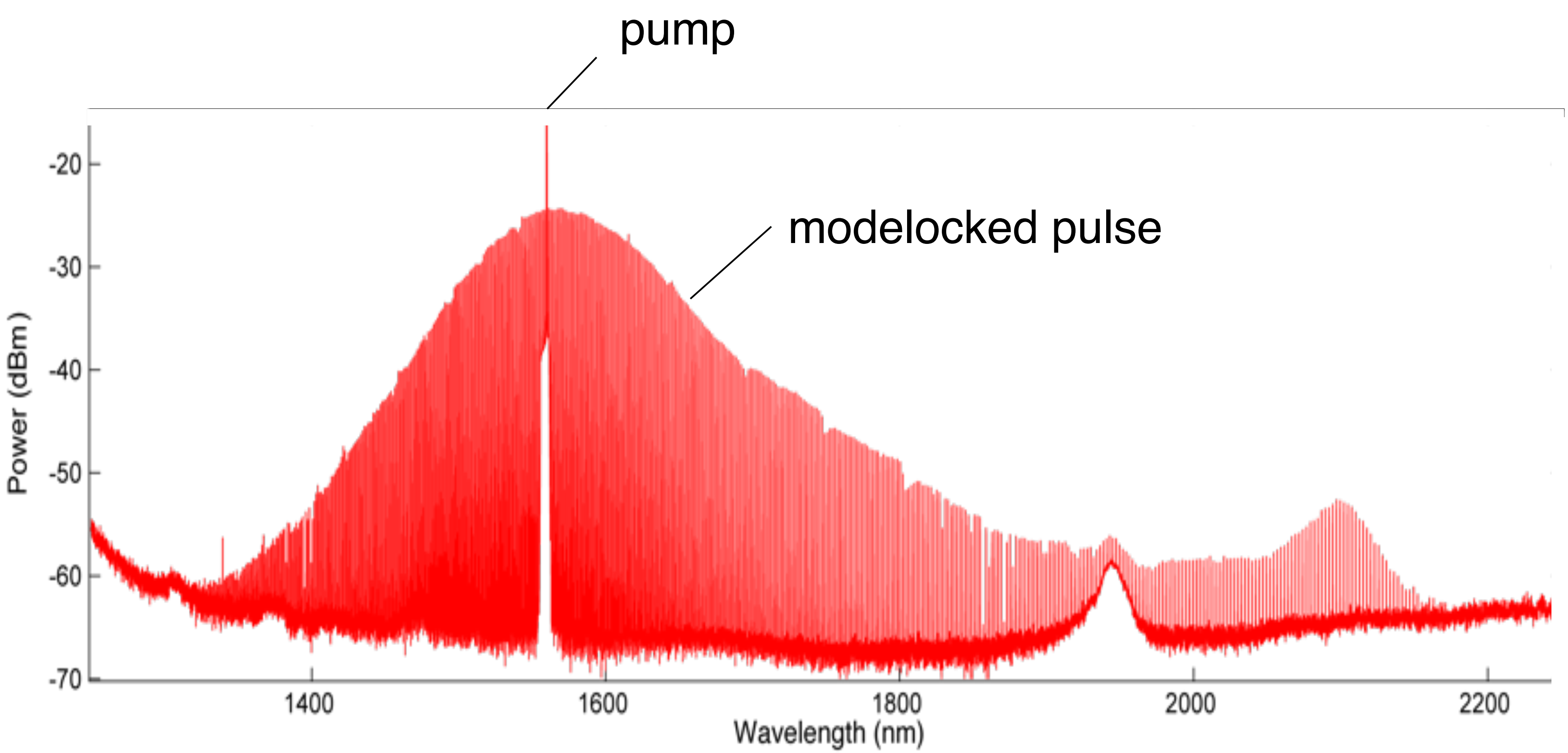
Review Article: Gaeta, Lipson, and Kippenberg, Nature Phot. (2019)

Comb Generation in Microresonators





Comb Generation in Microresonators



Theoretical Model for Comb Generation

- Lugiato-Lefever model: NLSE with ring-resonator B.C.

Lugiato and Lefever, (1987); Haelterman, et al.(1992); Leo, et al. (2010); Matsko, et al.(2011); **Coen, et al. (2013)** Chembo and Menyuk (2013); Lamont, Okawachi, & Gaeta (2013).

$$\frac{\partial}{\partial t}A = -(\alpha + i\delta)A - i\frac{L}{L_{DS}}\frac{\partial^2 A}{\partial \tau^2} + i\frac{L}{L_{NL}}|A|^2 A + \eta E_{in}$$

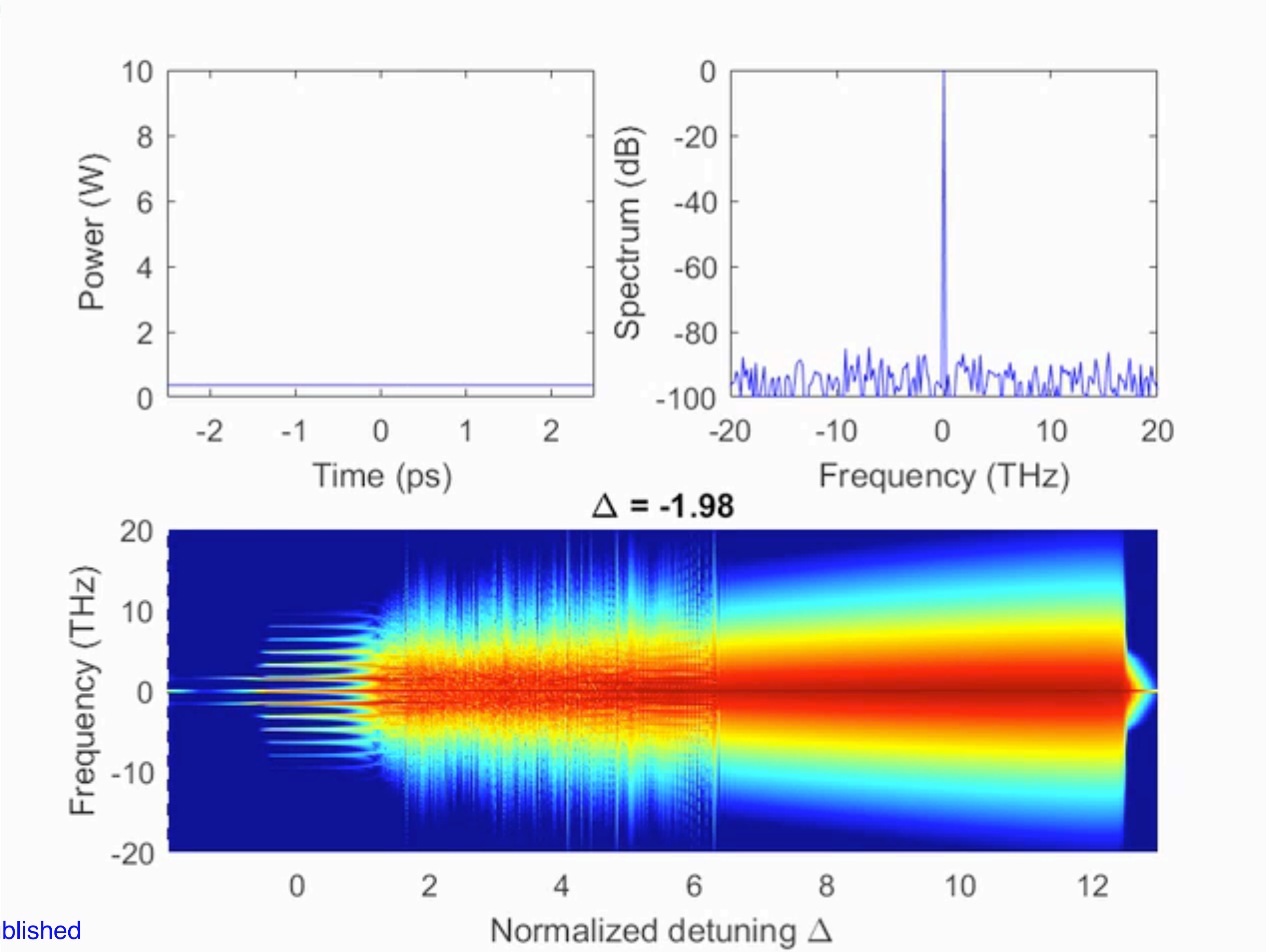
Cavity loss & detuning | Dispersion | Nonlinearity | Pump

<u>Dissipative soliton solutions exist</u>

$$A(\tau) \sim C_1 + C_2 \sum_{j=1}^{N} \mathrm{sech}\left[(\tau - \tau_j)/\tau_0\right]$$

Haelterman, Trillo, and Wabnitz, *Opt. Commun.* (1992).
Wabnitz, *Electron. Lett.* (1993).
Nakazawa, et al. (1988).
Herr, et al., Kippenberg, Nature Phot. (2014).

Simulations: Dynamics versus Detuning



Jang, unpublished

Microresonator-Based Frequency Combs

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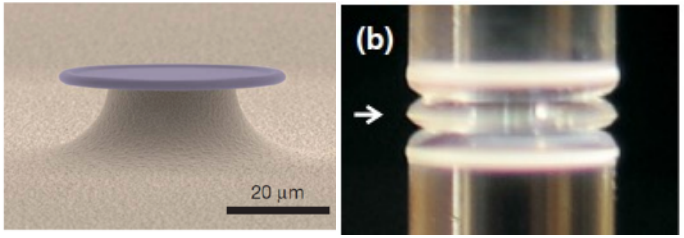
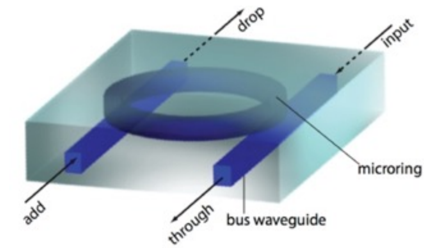


silica

Del' Haye, et al., Nature (2007)
Agha, et al., Opt. Express (2009)
Li, et al., PRL (2012)
Papp, et al., PRX (2013)

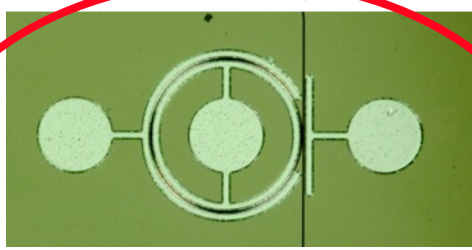
CaF_2, MgF_2, & quartz

Savchenkov, et al., PRL (2008)
Liang, et al., Opt. Lett. (2011)
Papp & Diddams, PRA (2011)
Herr, et al., Nature Photon. (2012)



high-index glass

Razzari, et al., Nature Photon. (2010).
Pasquazi, et al., Opt. Express (2013).

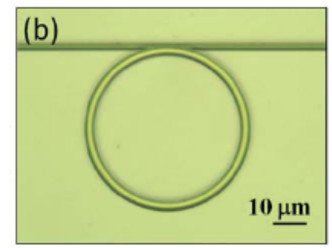


silicon

Griffith, et al., Nature Comm. (2014)
Yu, et al., Optica (2016)

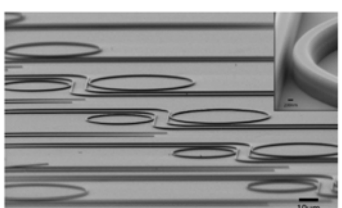
silicon nitride

Levy, et al., Nature Photon. (2010)
Ferdous, et al., Nature Photon. (2011)
Herr, et al., Nature Photon. (2012)



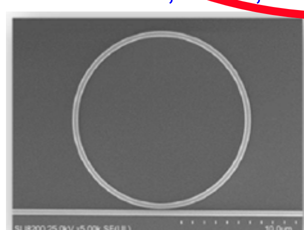
Al nitride

Jung, et al., Opt. Lett. (2013)



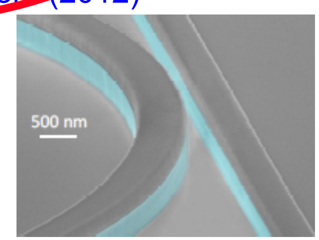
diamond

Hausmann, et al., Nature Phot. (2013)



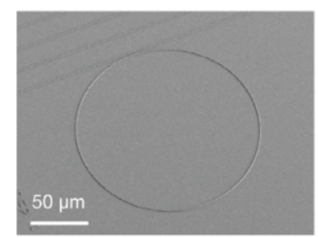
GaP

Wilson, et al., Nature Phot. (2018)



AlGaAs

Pu, et al., Optica (2016)



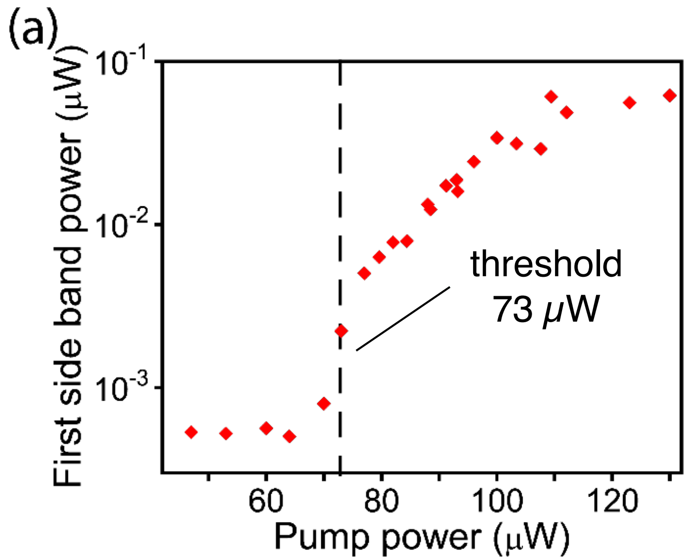
lithium niobate

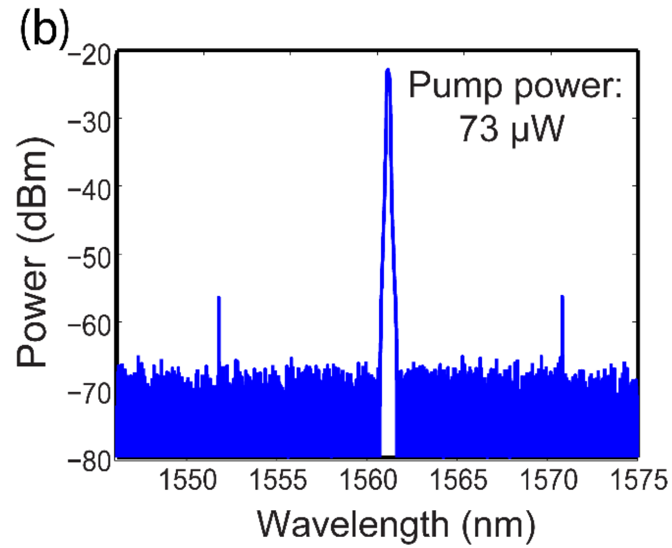
Wang, et al., Opt. Lett. (2018)
He, et al., Optica (2019)
Yu, et al., Light (2020)

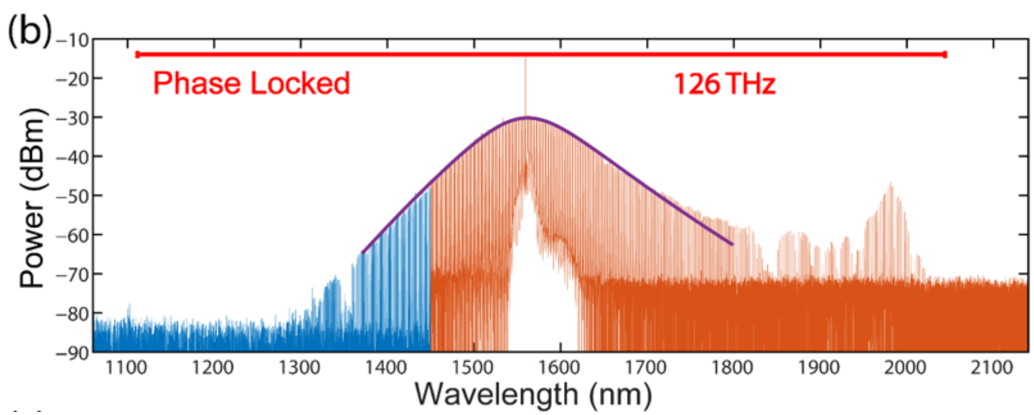
QUANTUM & NONLINEAR PHOTONICS GROUP

Ultrahigh-Q SiN Microresonators

COLUMBIA UNIVERSITY







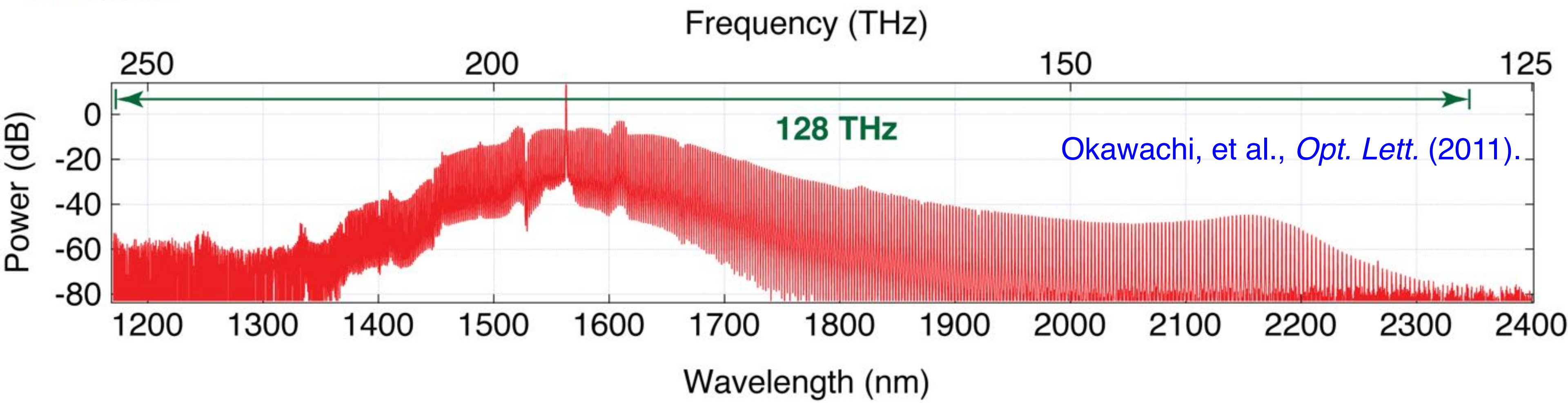
~ 2 mW

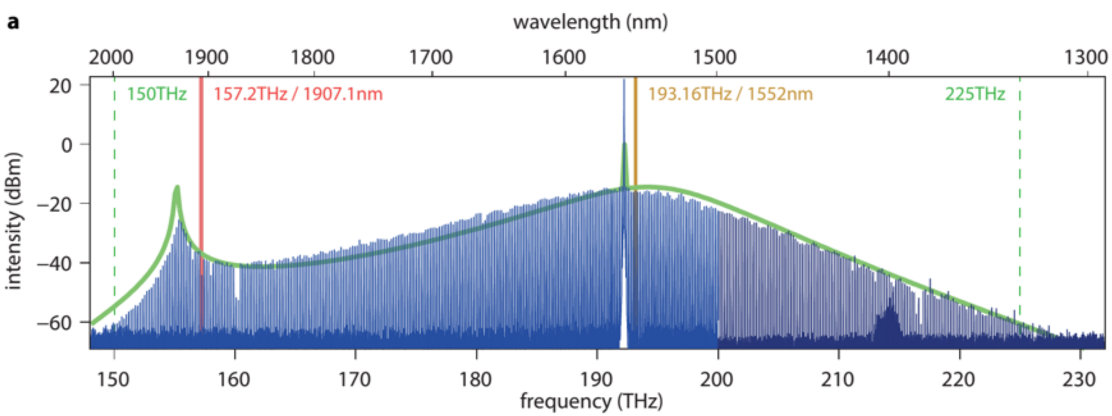
Ji, et al., Gaeta & Lipson, *Laser & Phot. Rev.* (2020).

Octave-Spanning Comb in Si_3N_4 Microresonators

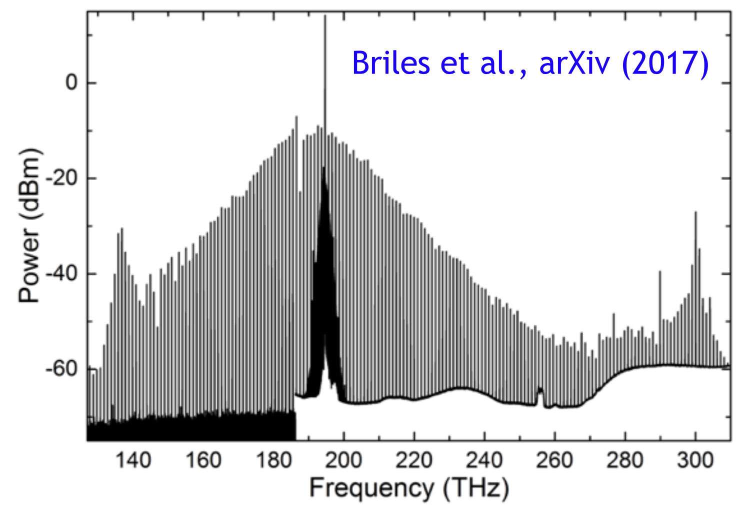
Quantum & Nonlinear Photonics Group

Columbia University





Brasch et al., Science (2016)



Modelocking & Dissipative Solitons in Microresonators

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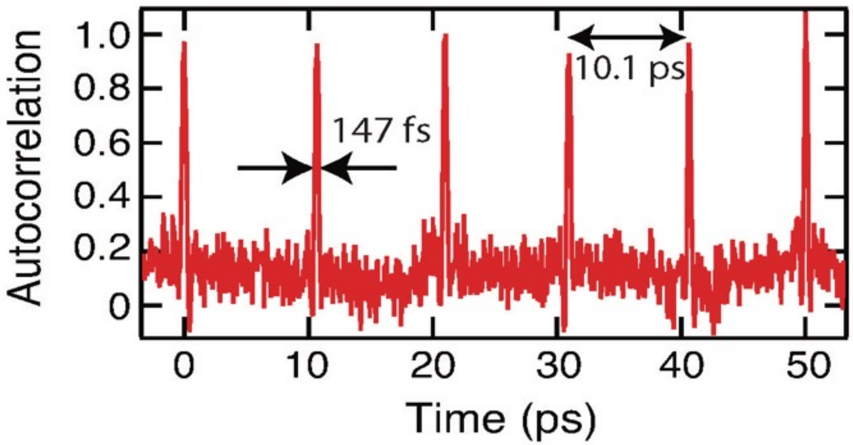
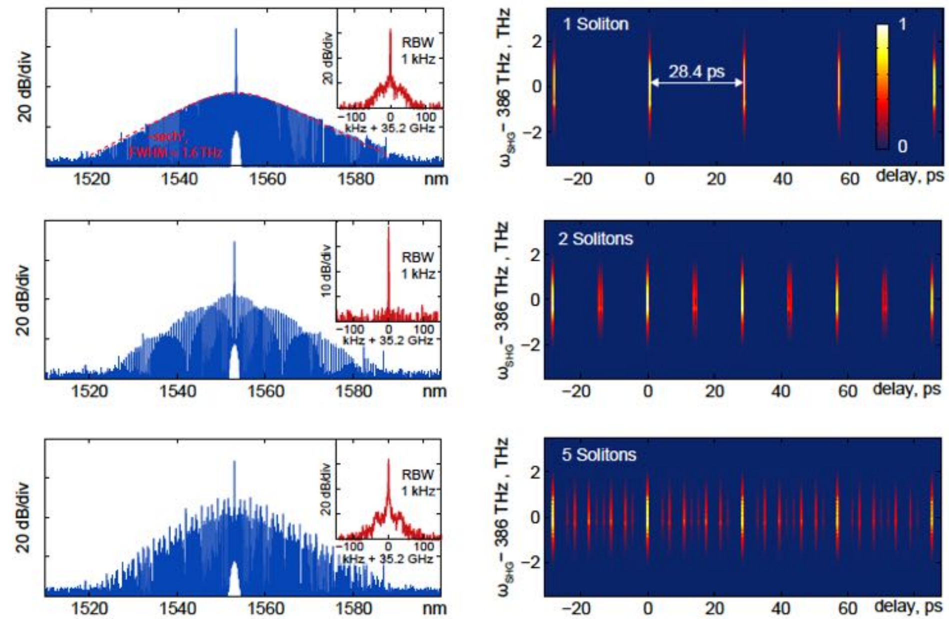
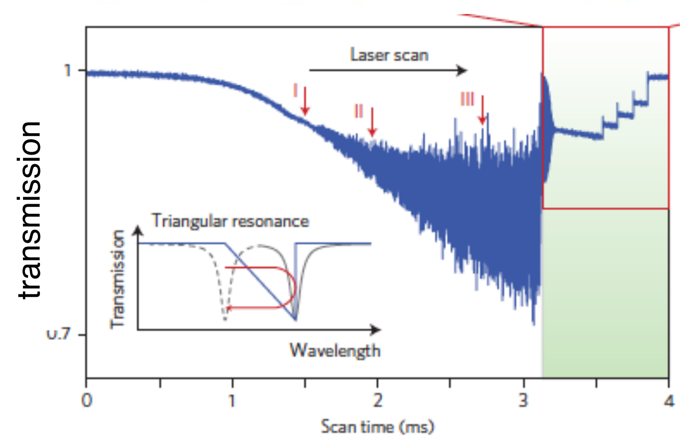


Saha et al, Opt. Express (2013).

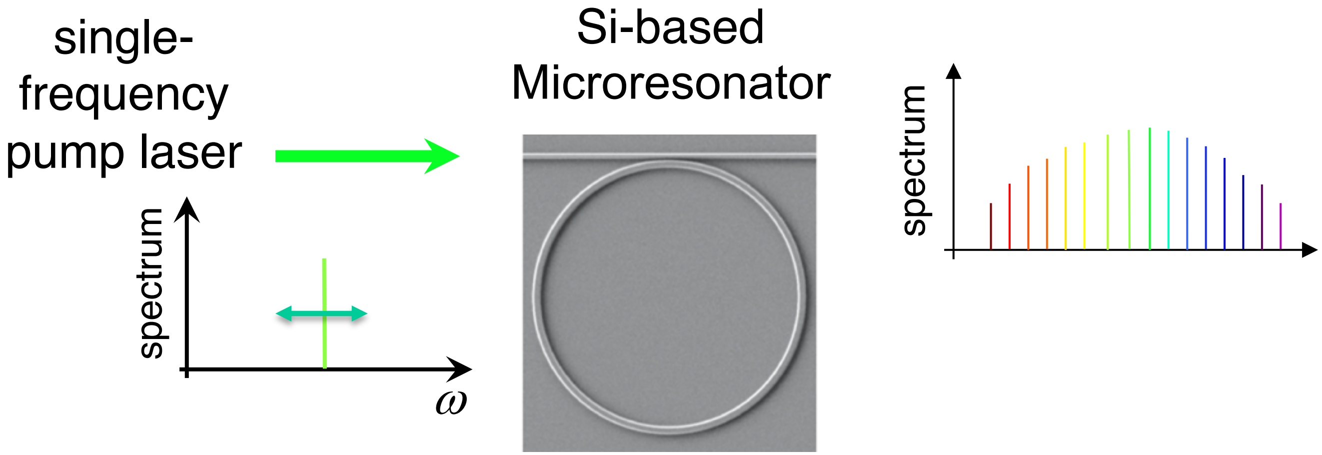


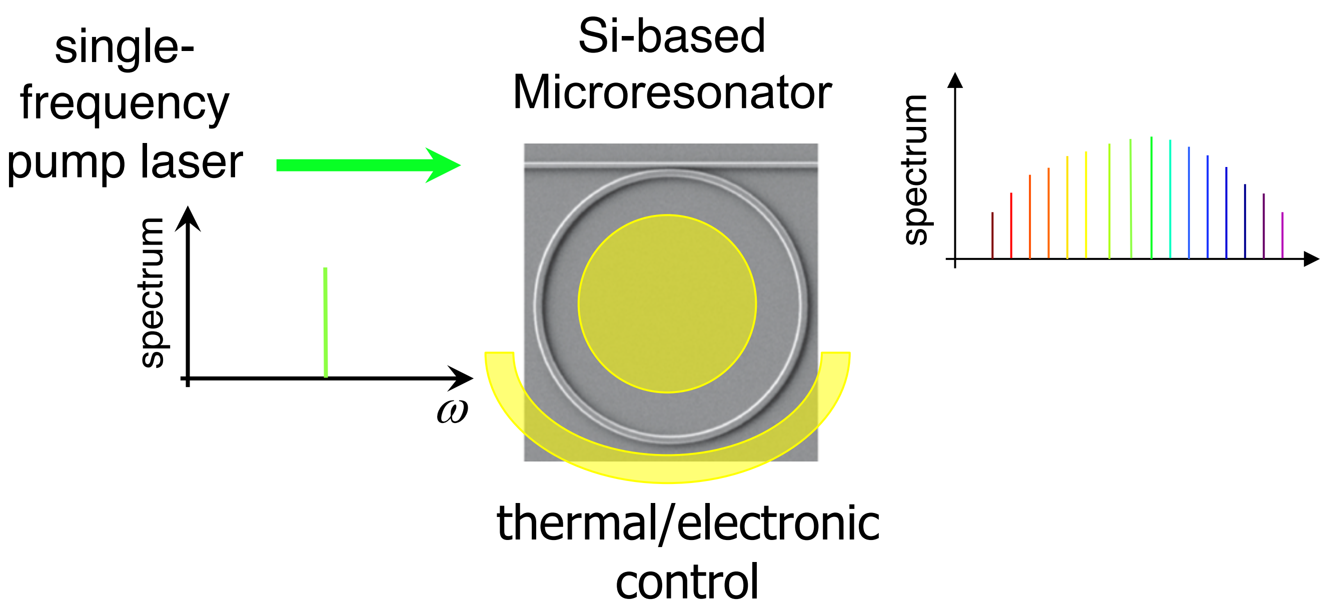


Review:
Kippenberg, Gaeta, Lipson, Gorodetsky
Science (2018).

Herr, et al., Kippenberg, *Nature Phot.* (2014)

Pump Detuning Control in Microresonators





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Experimental Setup

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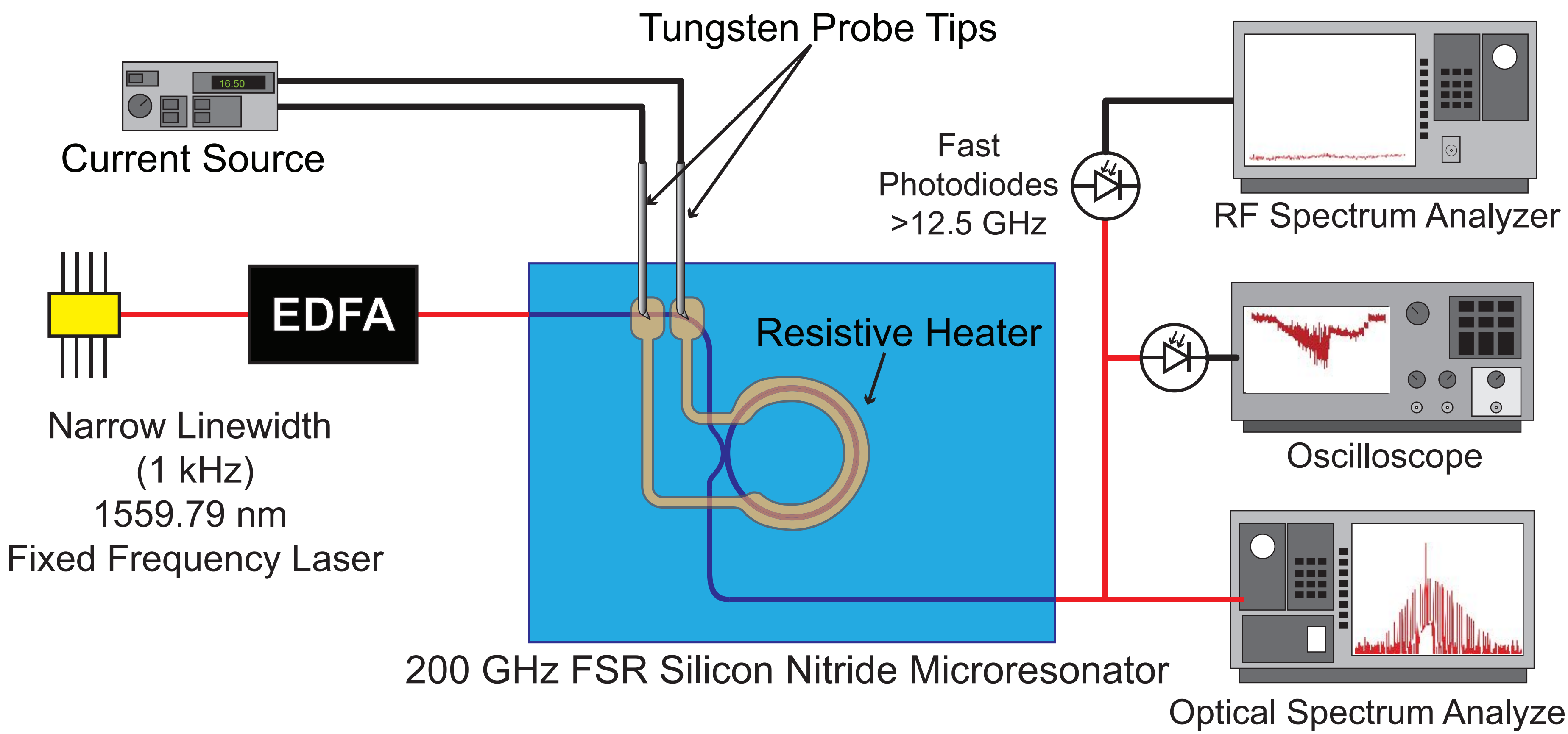
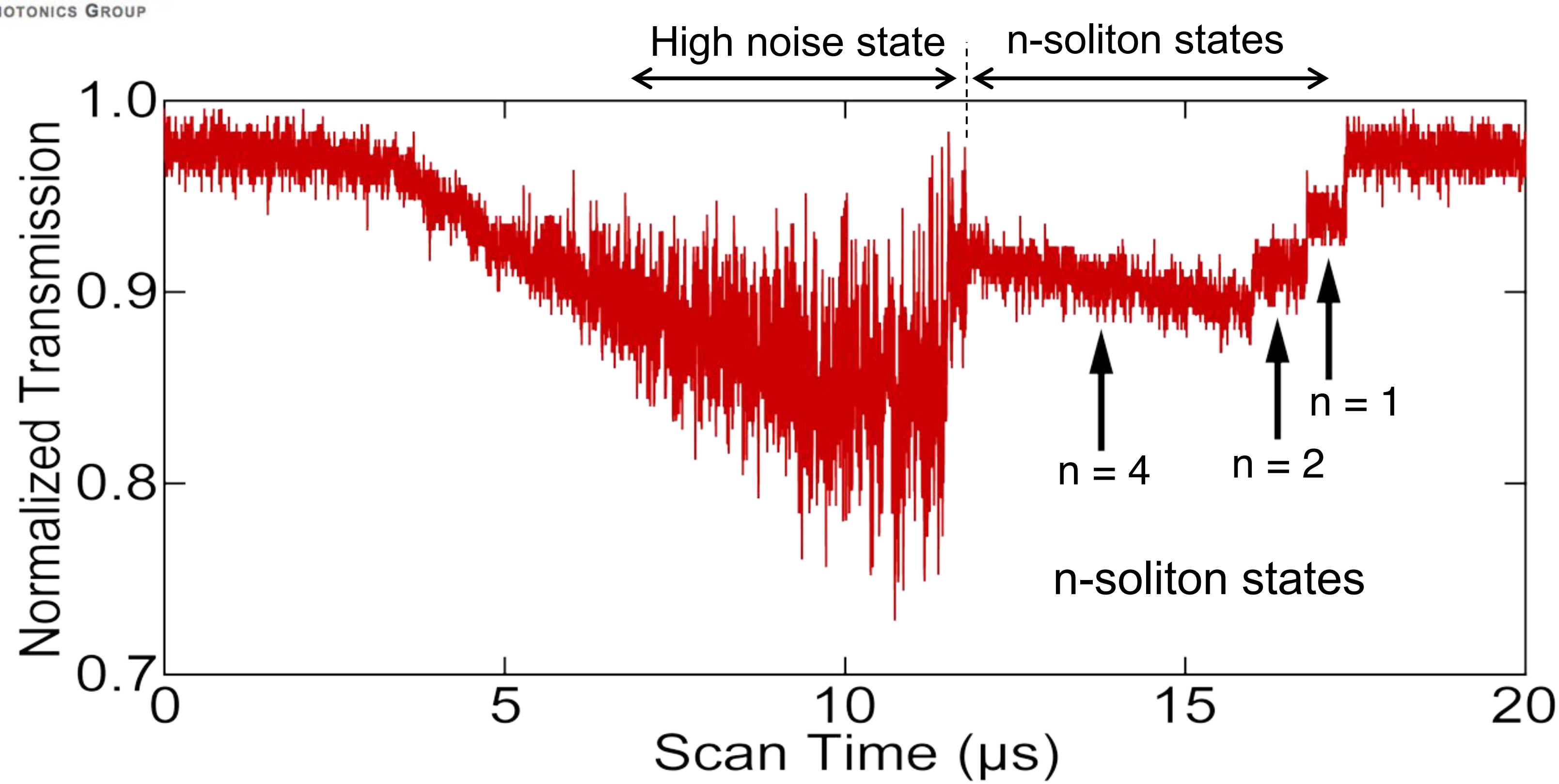


Joshi, et al. Opt. Lett. (2016)

Resonance Scan



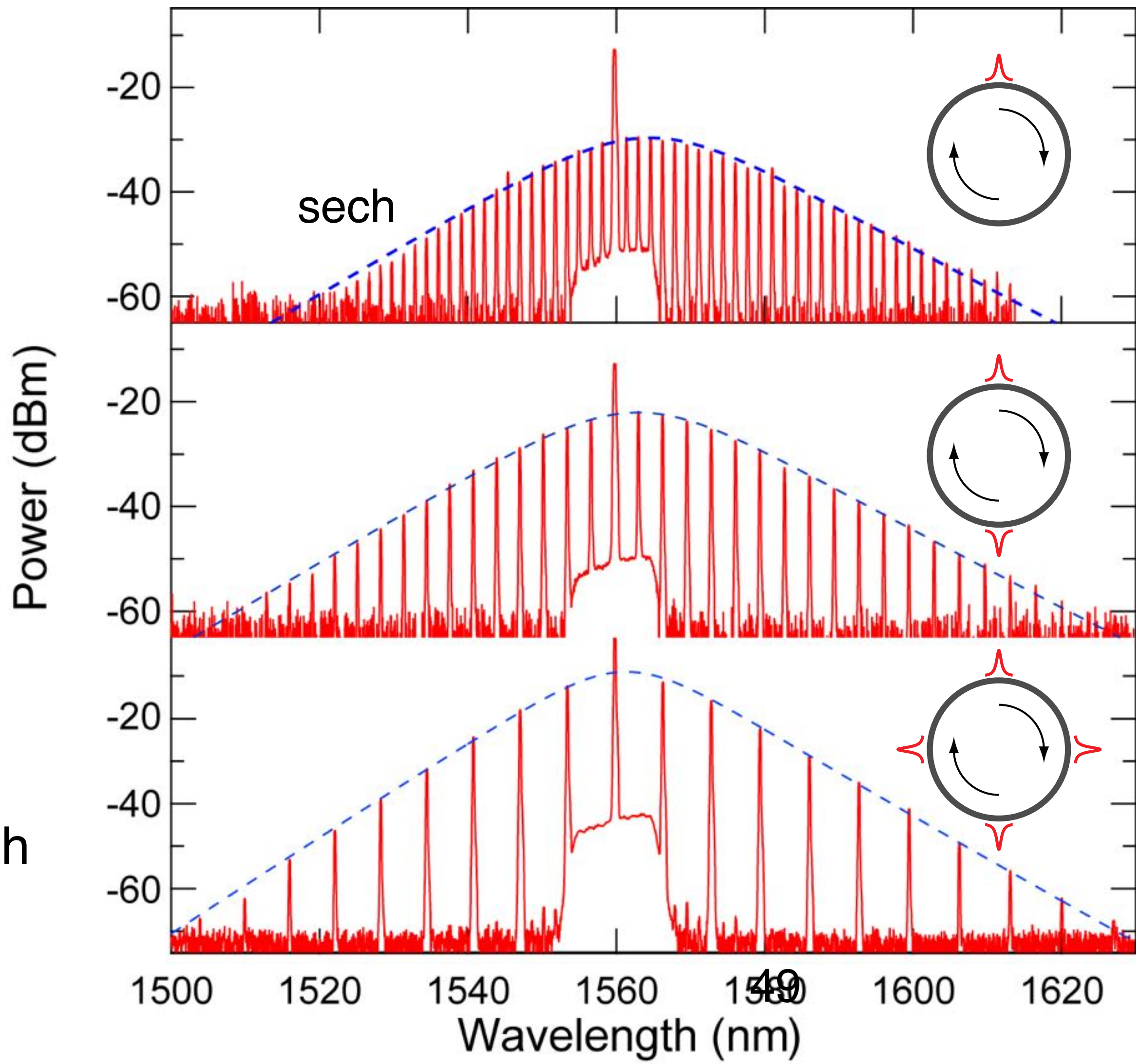
Joshi, et al., Lipson, Gaeta, *Opt. Lett.* (2016)

- Step-like features characteristic of soliton modelocking, similar to pump tuning Herr, et al. Nature Photon. (2014)

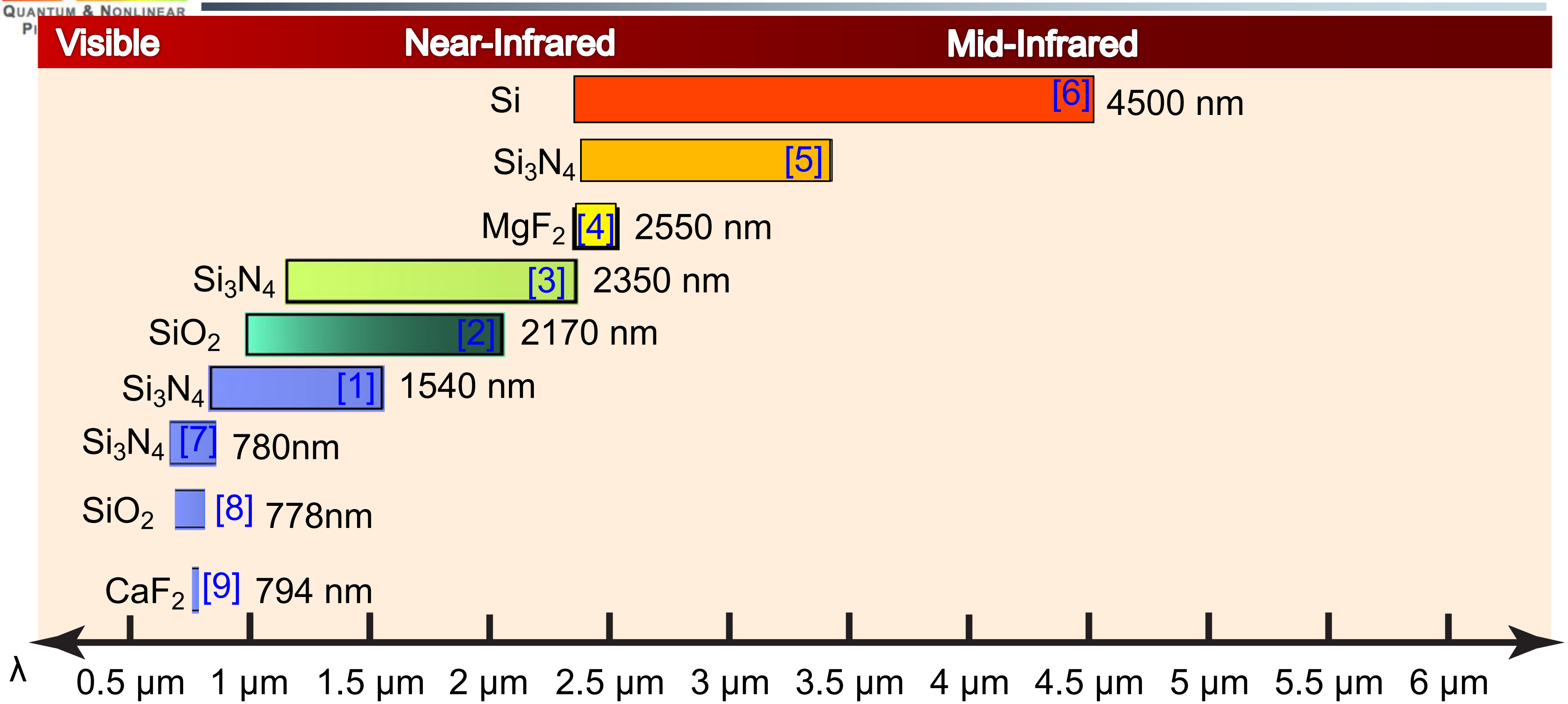
Multi-Soliton States

Spectral modulations due to relative positions of solitons

- Single Soliton – 1 FSR
- Two Soliton – 2 FSR
- Four Soliton – 4 FSR
- Show good agreement with sech² envelope

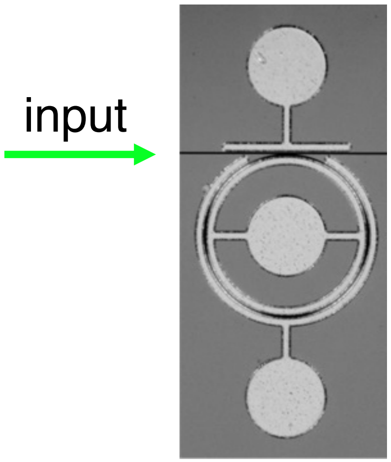


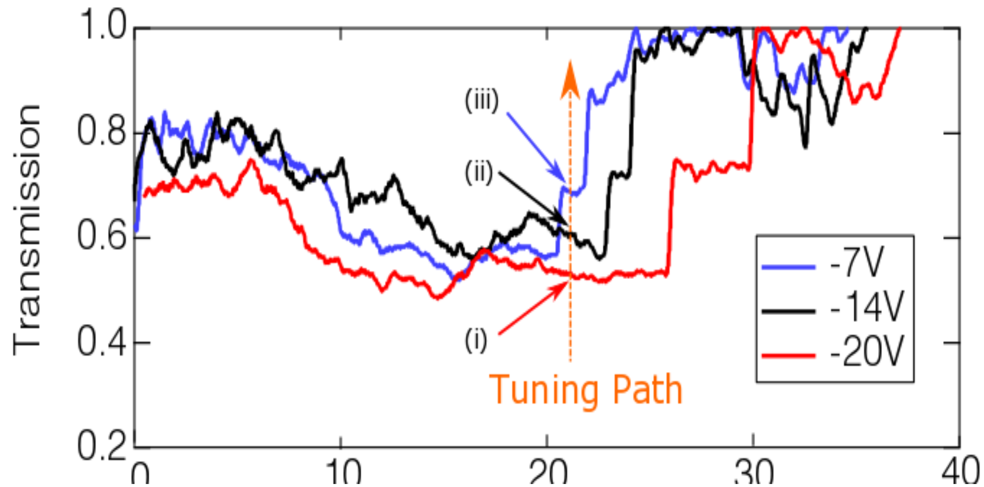
Microresonator Comb Spectral Coverage

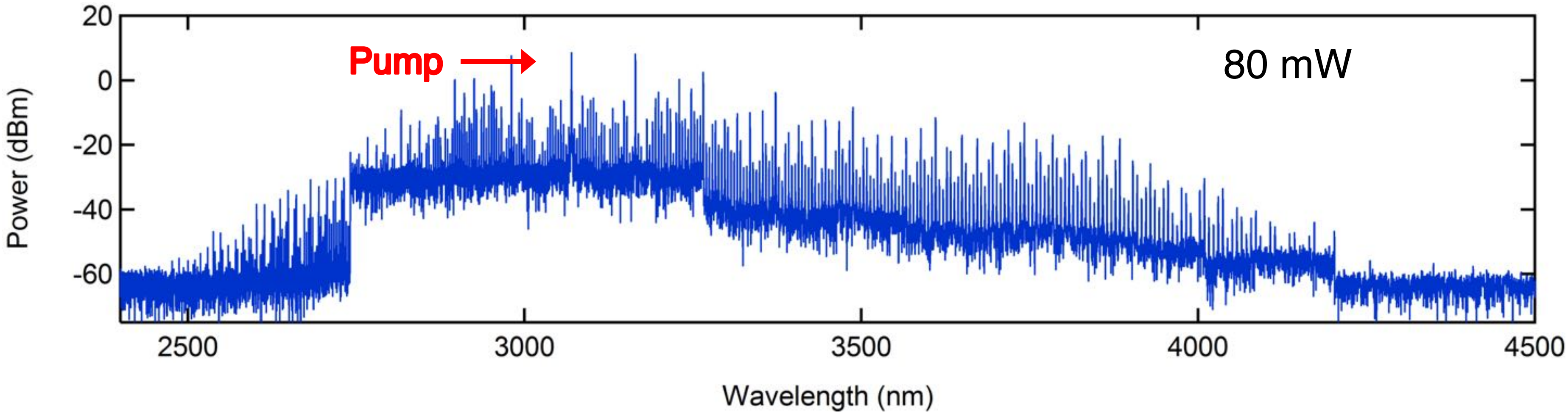


[1] Saha, et al., Lipson & Gaeta OE (2013); Luke, *et al.*, Gaeta & Lipson, OE (2016).
[2] Del'Haye, *et al.*, and Kippenberg, Phys. Rev. Lett. (2011).
[3] Okawachi, *et al.*, Lipson & Gaeta, Opt. Lett. (2011); Okawachi, *et al.*, Lipson & Gaeta, Opt. Lett. (2013).
[4] Wang, *et al.*, and Kippenberg, Nature Comm. (2012).
[5] Luke, *et al.*, Gaeta and Lipson, Opt. Lett. (2015).
[6] Griffiths, *et al.*, Gaeta & Lipson, Nat. Comm. (2015); Yu, et al., Lipson & Gaeta, Optica (2016).
[7] Donvalkar *et al.*, Gaeta and Lipson, CLEO (2017).
[8] Lee, et al. Vahala, arXiv (2017)
[8] Savchenkov, *et al.*, Nat. Phot. (2011).

Mid-IR Soliton Modelocked Combs







- High pump-to-comb conversion efficiency (40%)

Yu, et al., Lipson & Gaeta, *Optica* (2016)

Synchronization of Microresonator Combs

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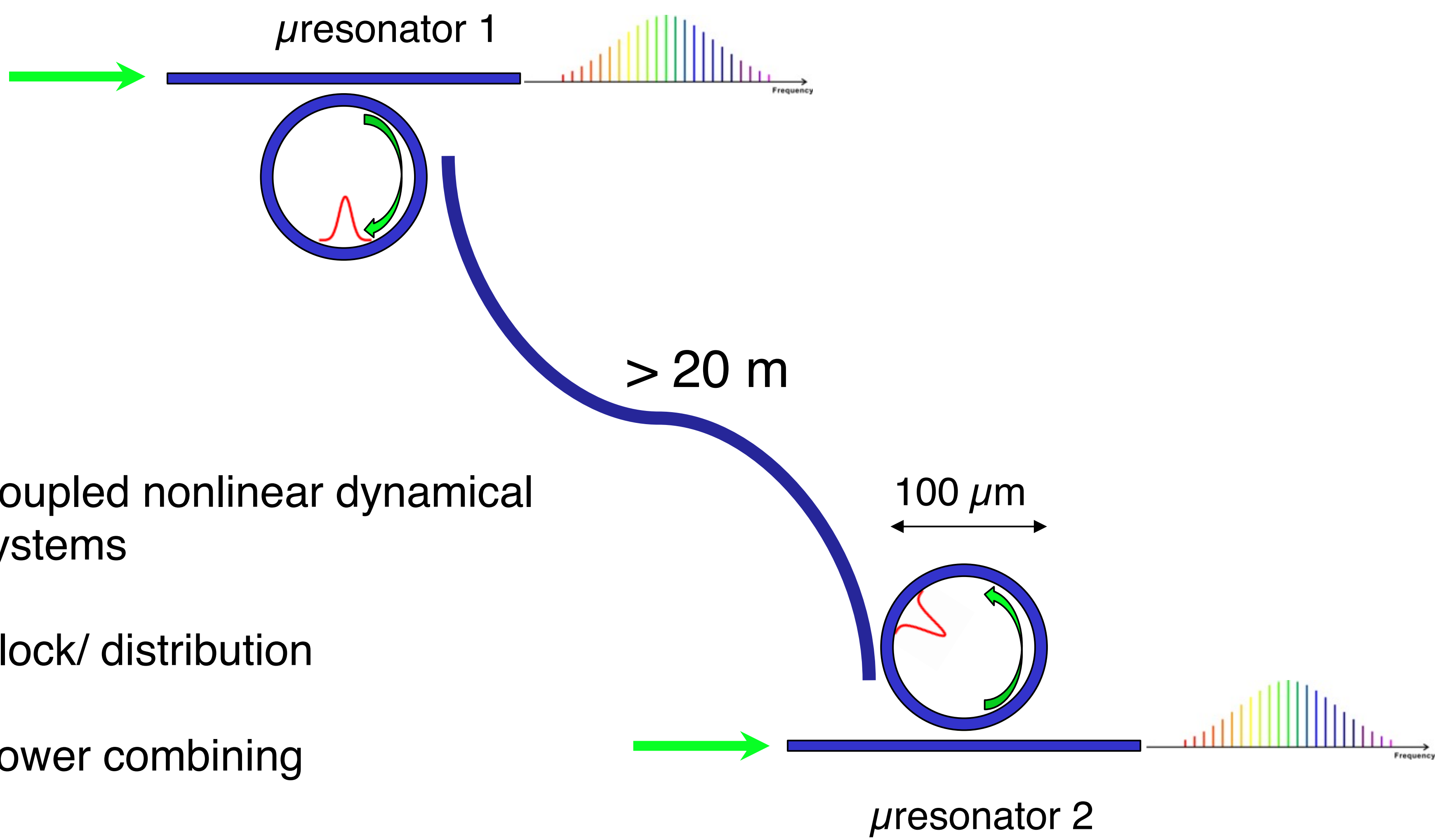
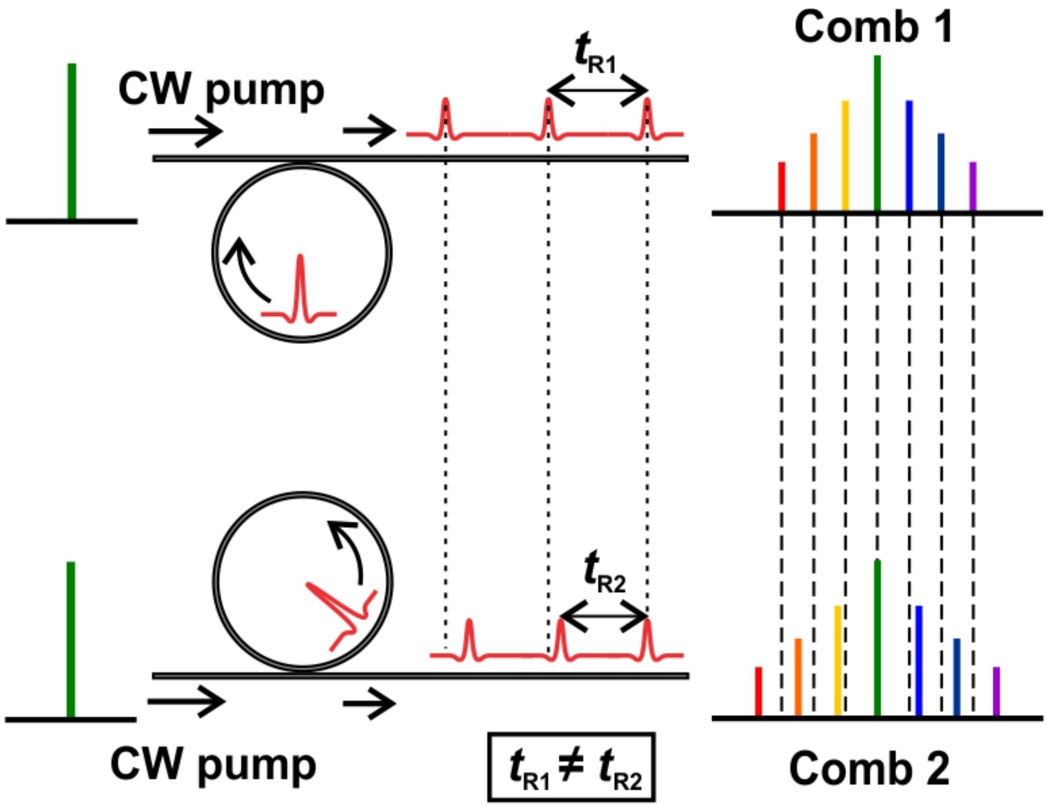
Columbia University



- Coupled nonlinear dynamical systems
- Clock/ distribution
- Power combining
- Microwave mixing applications

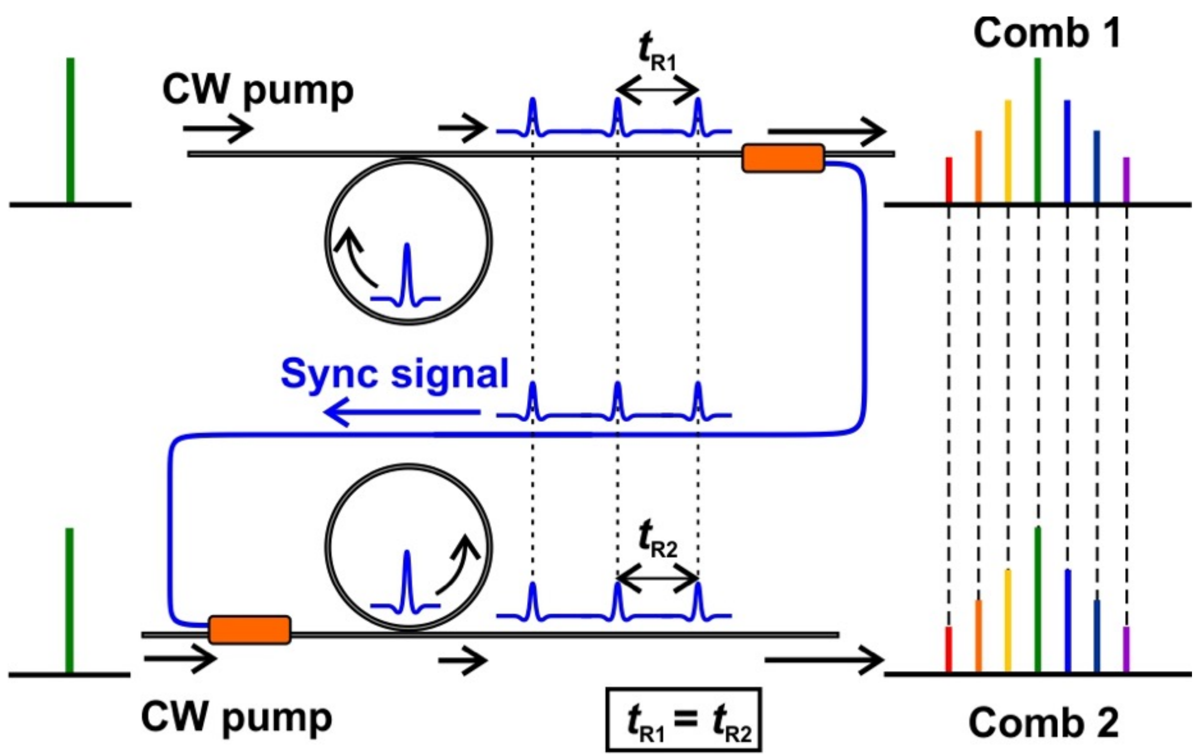
Uncoupled Microresonators

- **Comb spacing mismatched**
  1) Fabrication uncertainty
  2) Environmental fluctuations

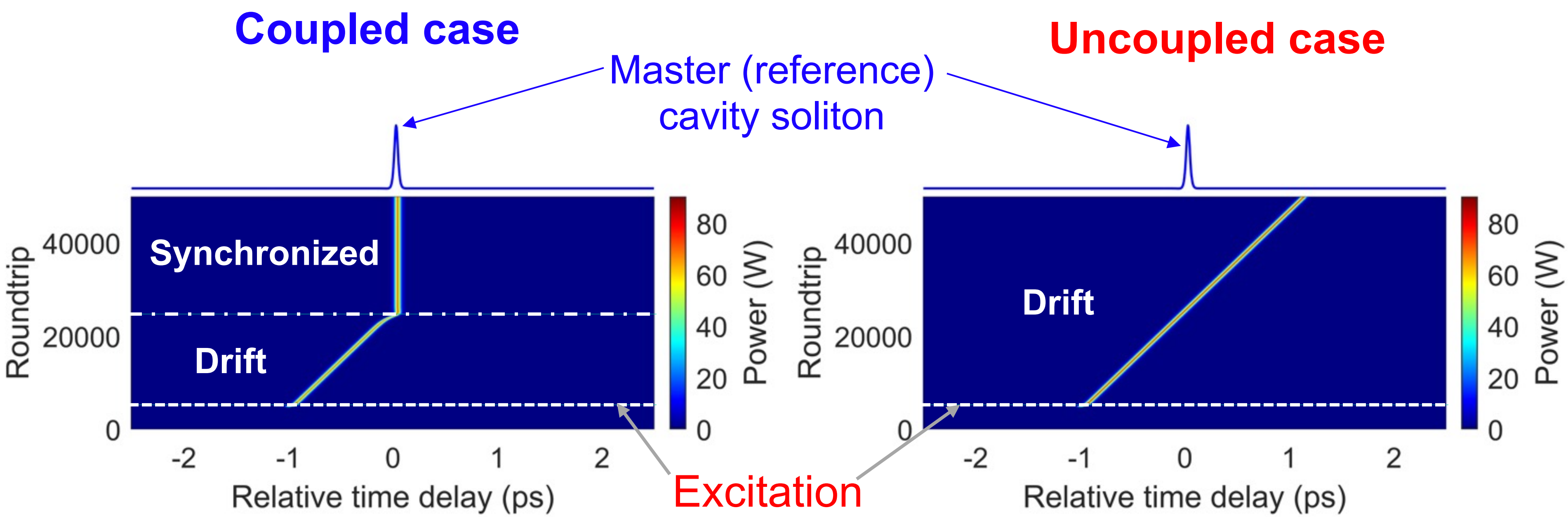


Coupled and Synchronized Microresonators

- Couple <1% of output from one microresonator to other
- Timing of cavity solitons become synchronized

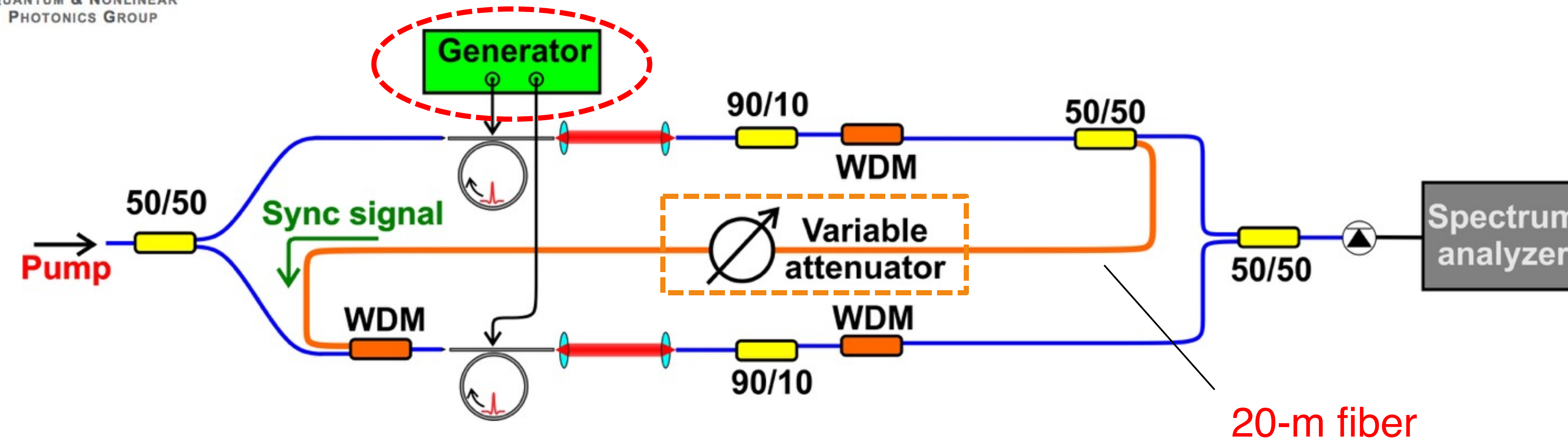


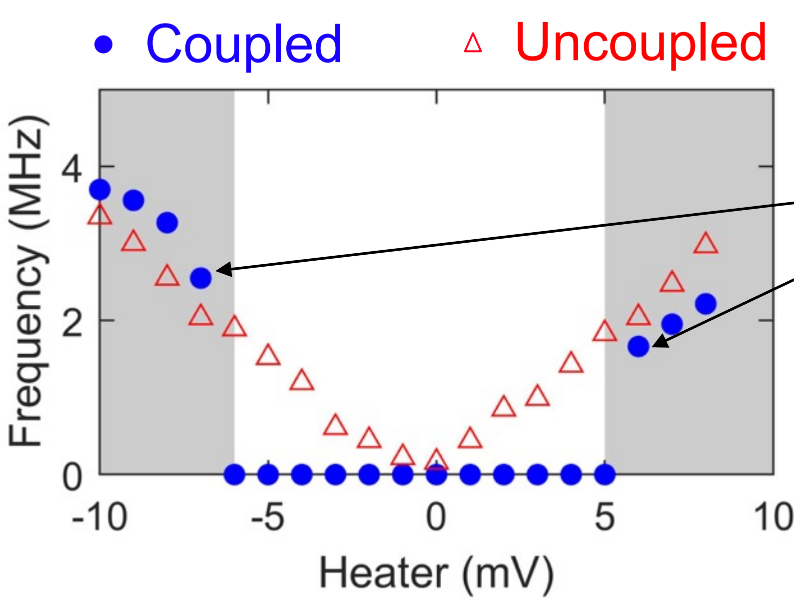
Simulations – Coupled LLE



- Natural drift rate is 2 MHz for both cases.

Experimental Characterization – Beat-Note Measurement

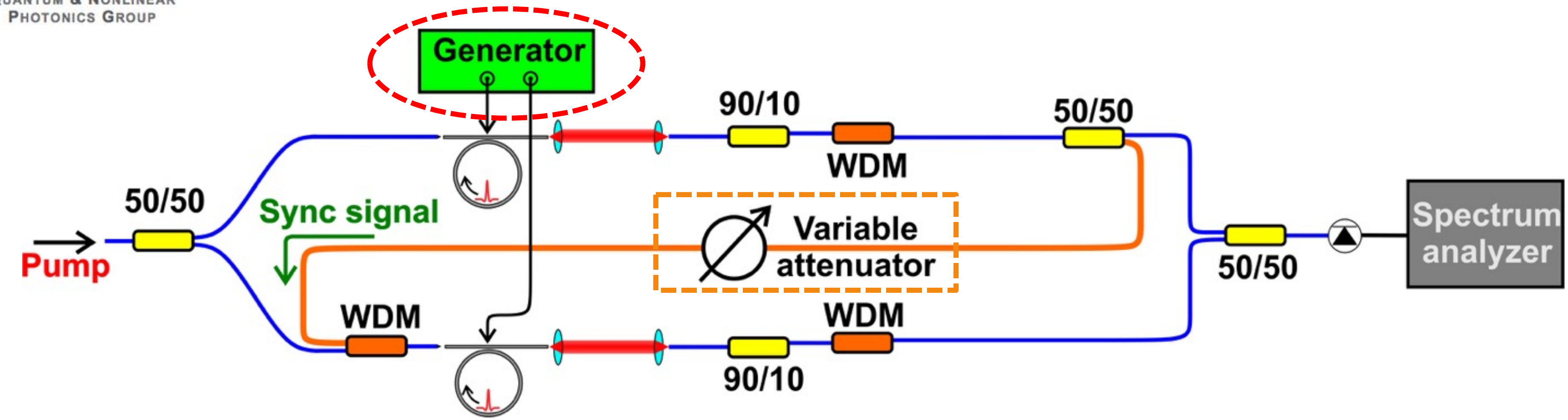


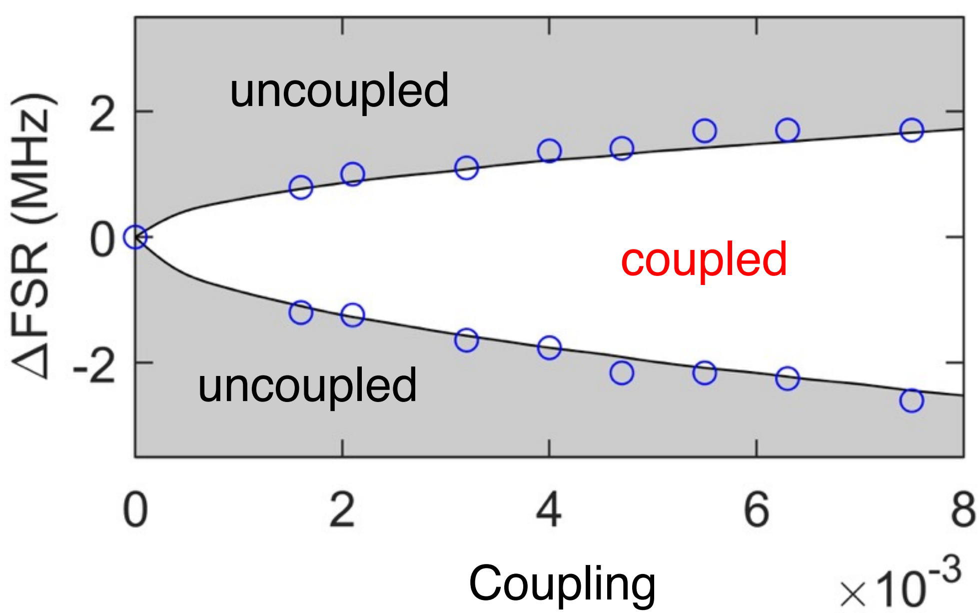


- Allowed mismatch: 2.6 MHz and 1.7 MHz
- Numerical predictions: 2.5 MHz and 1.5 MHz

Jang, et al. Lipson & Gaeta, Nature Phot. (2018)

Experimental Characterization – Beat-Note Measurement





- Allowed mismatches for varying transmission

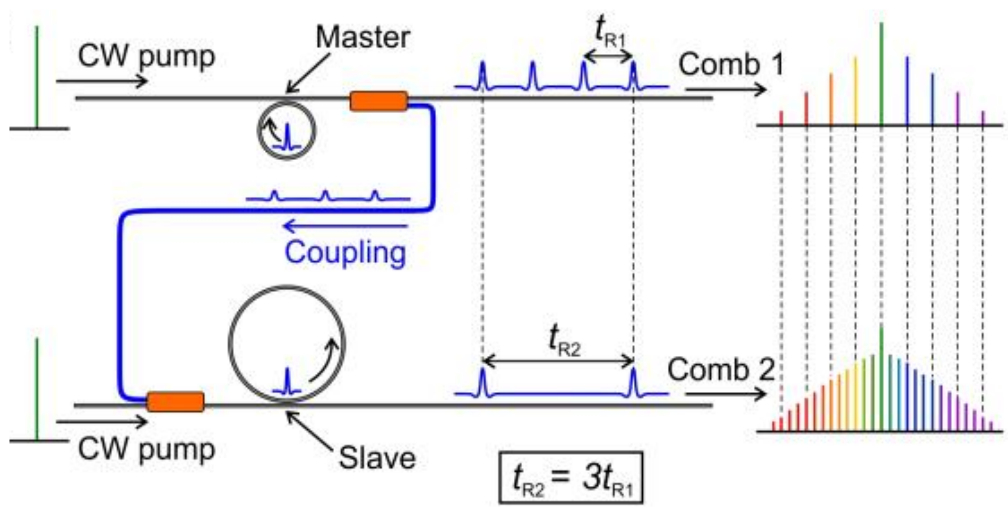
○ **Experimental**

— **Numerical**

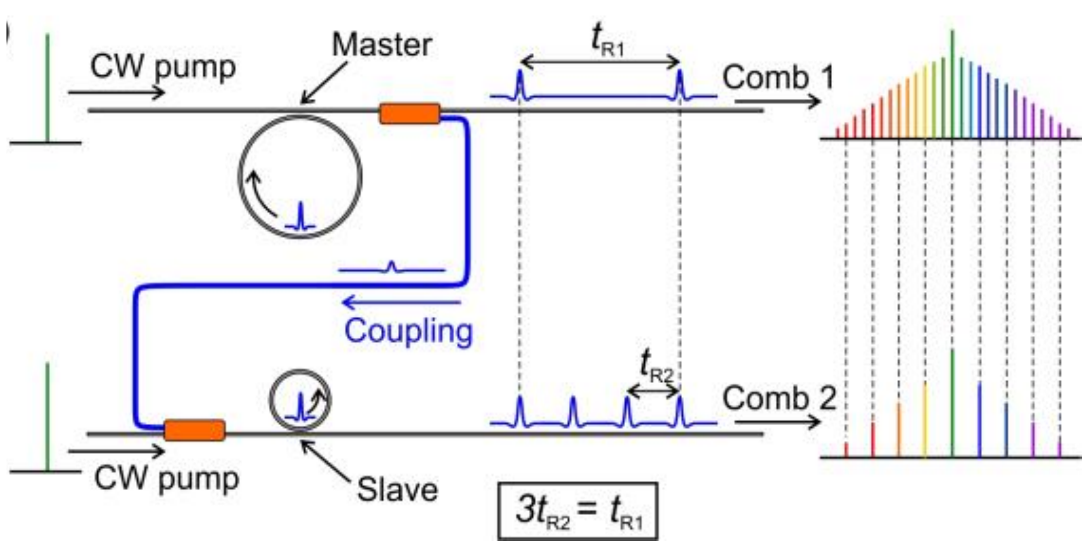
Jang, et al. Lipson & Gaeta, Nature Phot. (2018)

Harmonic & Sub-Harmonic Synchronization

Sub-Harmonic Synchronization



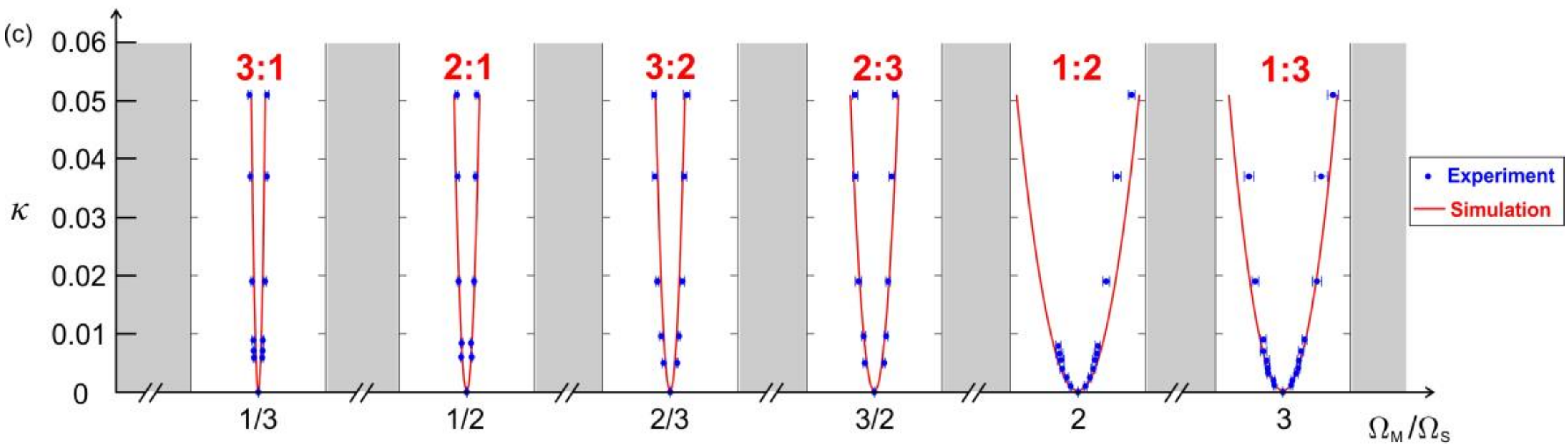
Harmonic Synchronization



Synchronization Regimes

Sub-Harmonic Synchronization

Harmonic Synchronization

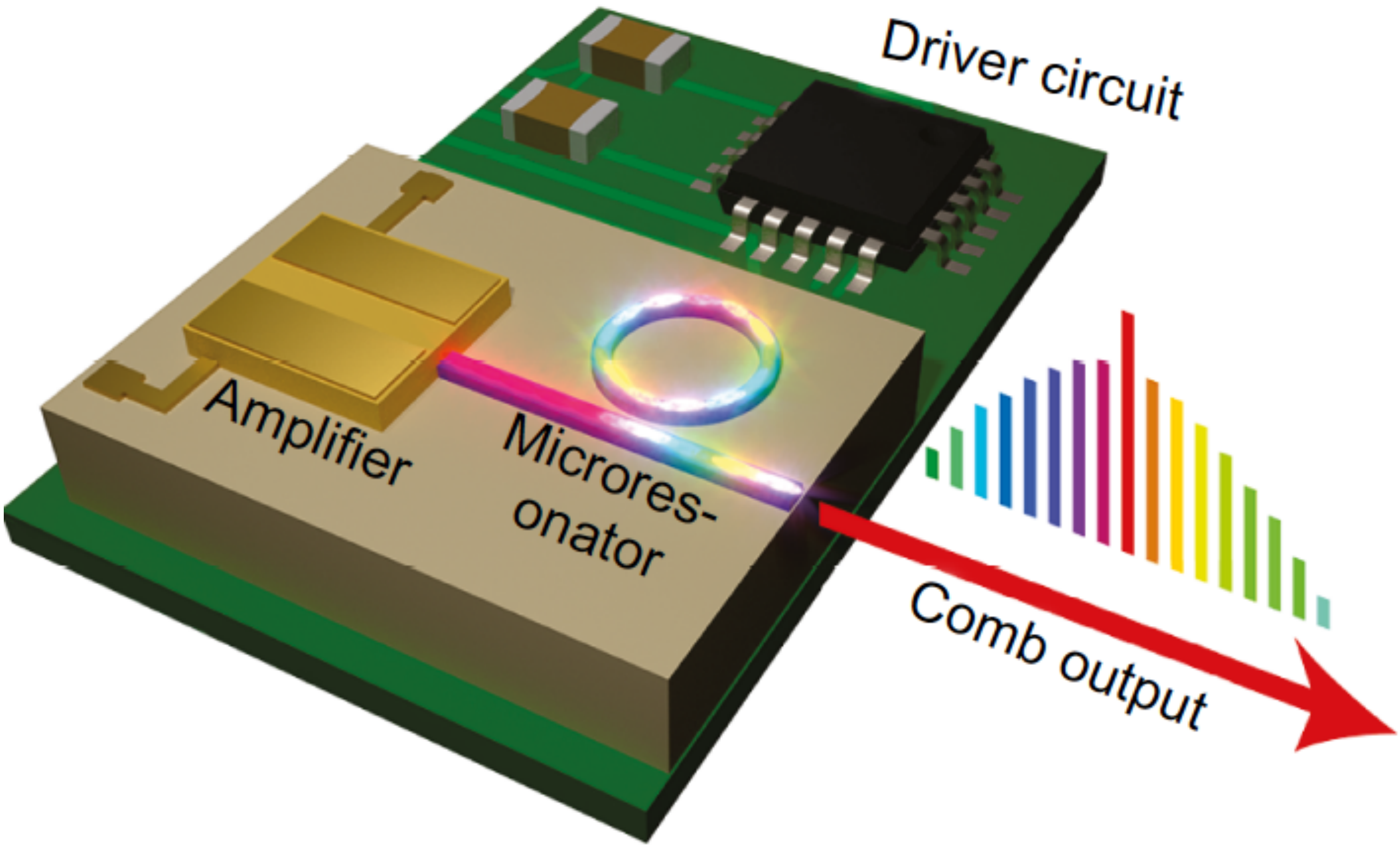


Jang, et al. Lipson & Gaeta, PRL (2019)

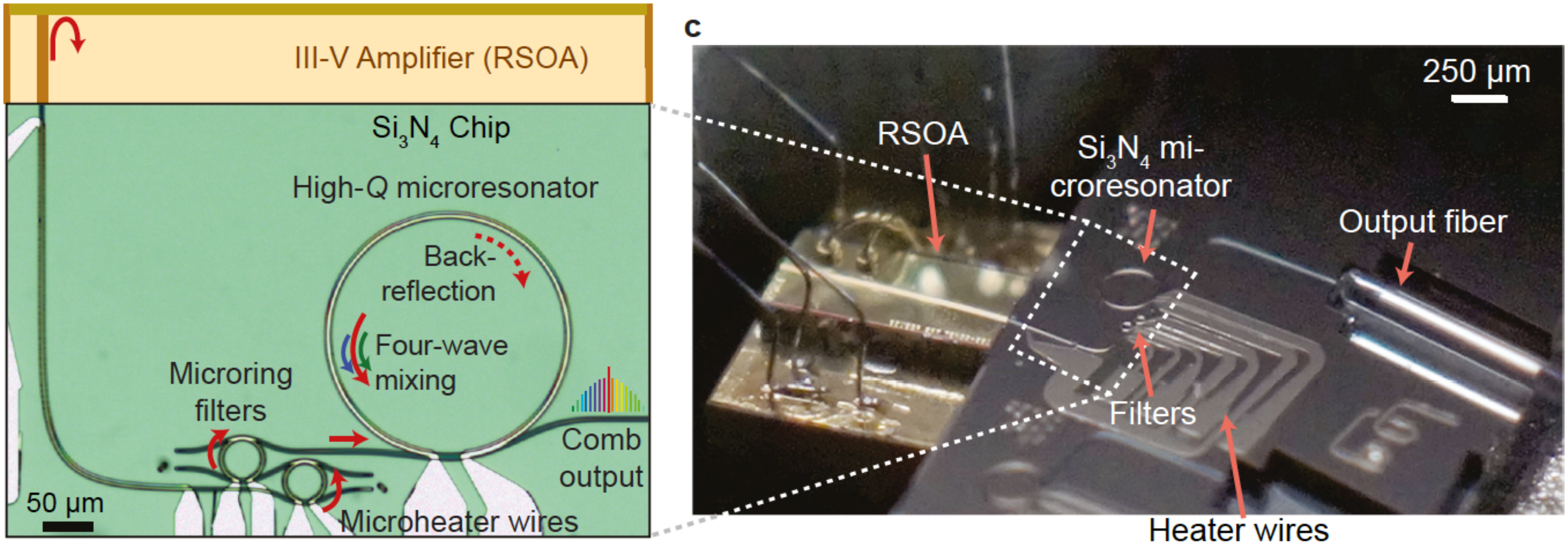
Quantum & Nonlinear Photonics Group

Vision for Integrated Kerr Comb Source

Columbia University



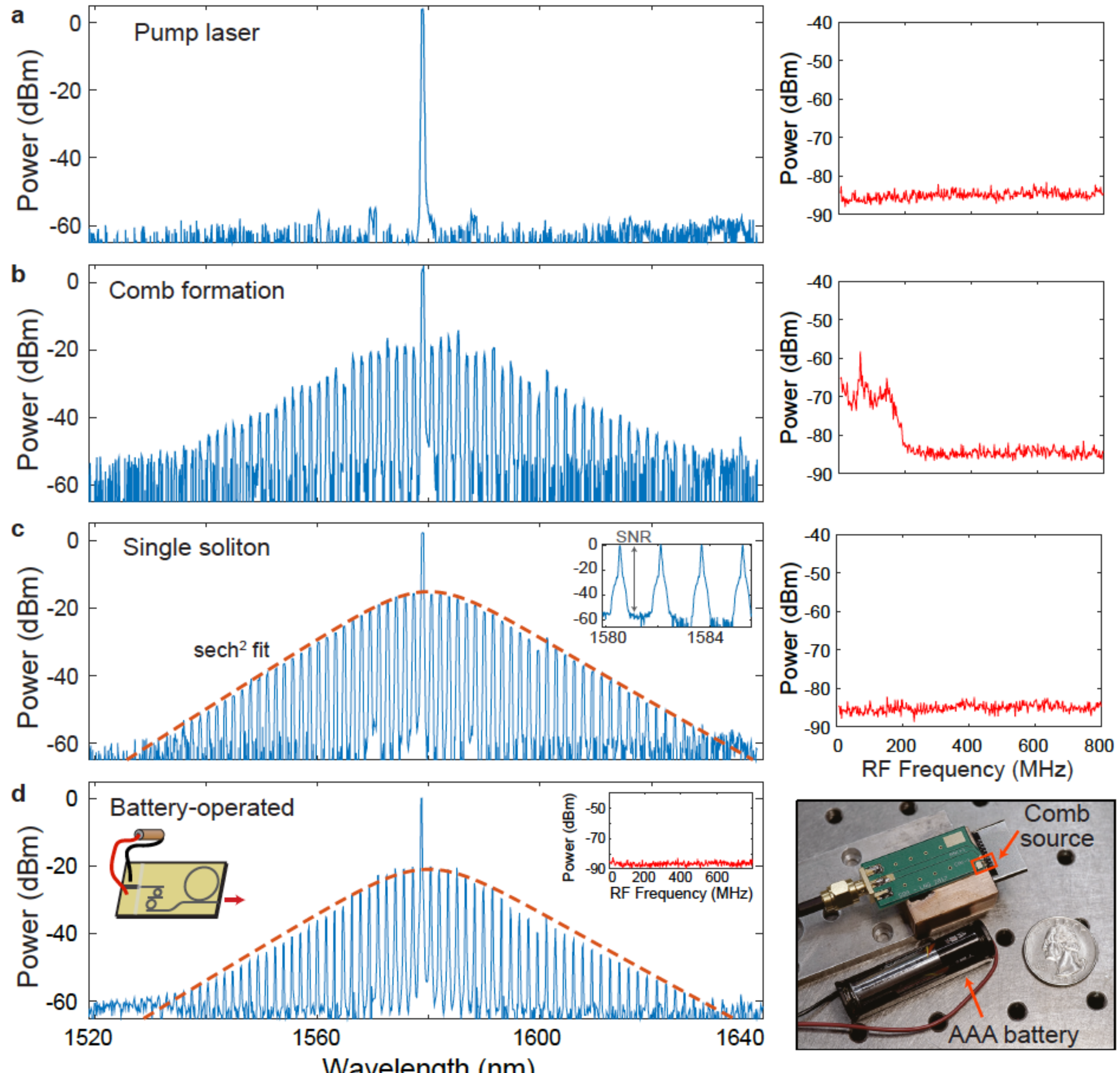
Realization Integrated Kerr Comb Source



Stern, et al. Gaeta & Lipson, Nature (2018)

Recent work: Shen et al., Kippenberg, Vahala, & Bowers, Nature (2020)

Fully Integrated Comb Generator



98 mW electrical power

Stern, et al. Gaeta & Lipson, Nature (2018)

Acknowledgements

Quantum & Nonlinear Photonics Group

Columbia University

Jae Jang
Chaitali Joshi
Chaitanya Joshi
Bok Kim
Alexander Klenner
Yoshi Yamamoto
Mengjie Yu
Yun Zhao

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