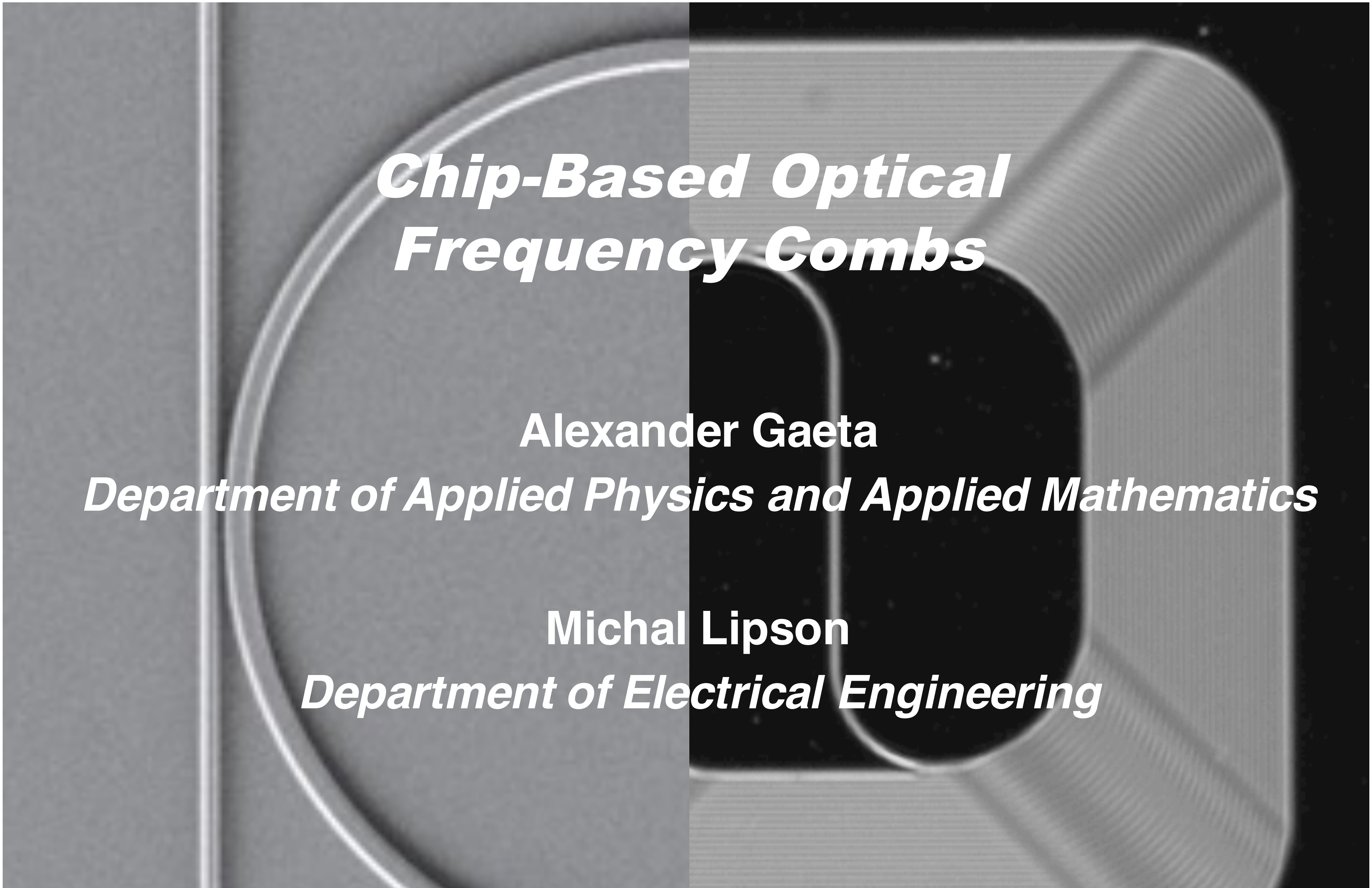


Chip-Based Optical Frequency Combs

Alexander Gaeta

Department of Applied Physics and Applied Mathematics

Michal Lipson

Department of Electrical Engineering

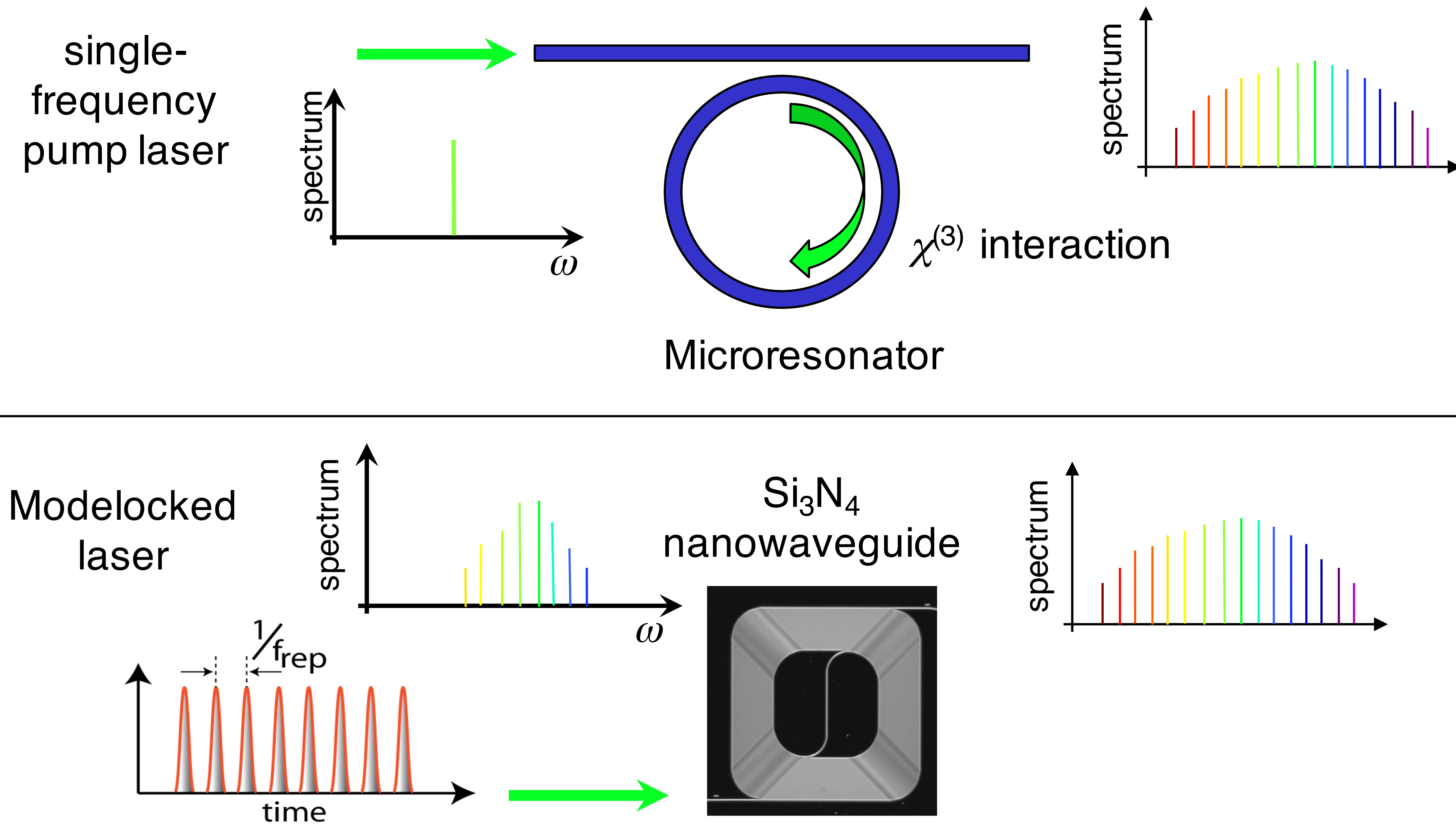
COLUMBIA | ENGINEERING

The Fu Foundation School of Engineering and Applied Science

KISS Frequency Comb Workshop

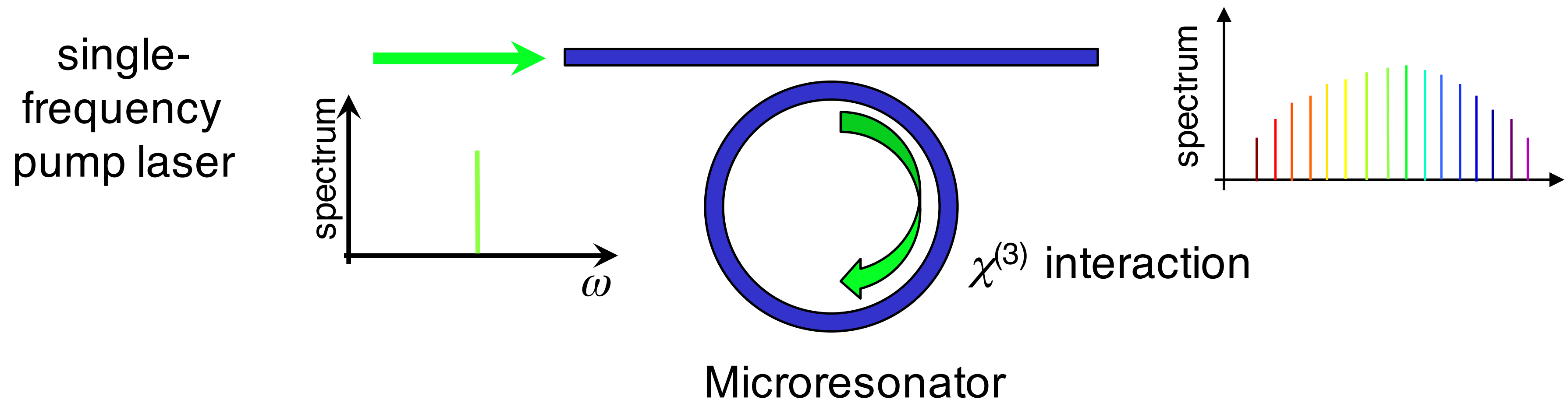
Cal Tech, Nov. 2-5, 2015

Chip-Based Comb Generation



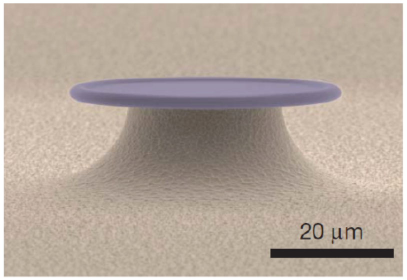
- Origin of combs can be traced to ***<u>four-wave mixing (FWM)</u>***
- Requires small anomalous group-velocity dispersion

Chip-Based Comb Generation



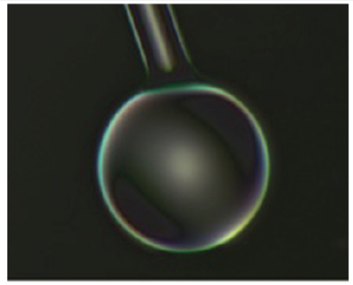
- Origin of combs can be traced to ***four-wave mixing (FWM)***
- Requires small anomalous group-velocity dispersion

Microresonator-Based Parametric Combs



silica µ-toroids

Del' Haye *et al.*, Nature (2007).
Del' Haye *et al.*, PRL (2008).

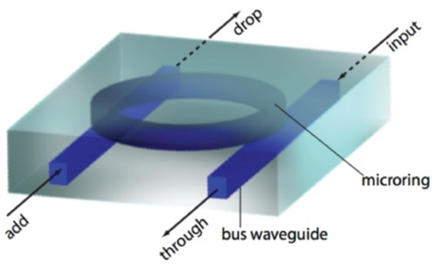


silica µ-spheres

Agha *et al.*, Opt. Express (2009).

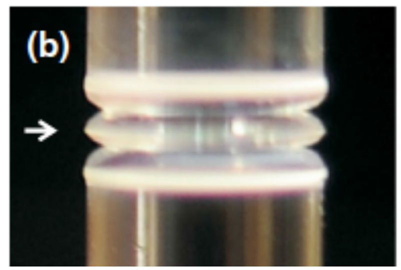
CaF_2, MgF_2, & quartz

Savchenkov *et al.*, PRL (2008).
Liang *et al.*, Opt. Lett. (2011).
Papp & Diddams, PRA (2011).
Herr *et. al.*, Nat. Phot. (2012).



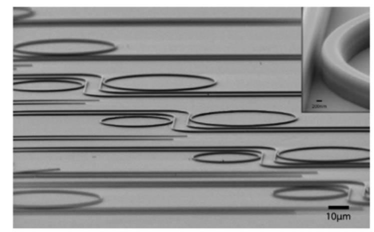
high-index glass µrings

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



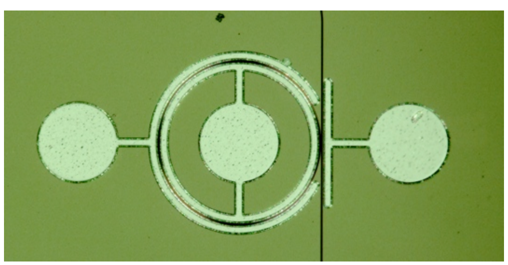
silica disks & rods

Li *et al.*, PRL (2012)
Papp, *et al.*, PRX (2013)



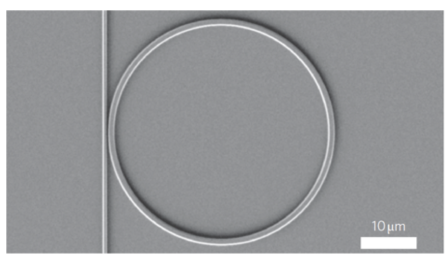
diamond

Hausmann *et al.*, Nat. Photon. (2013).



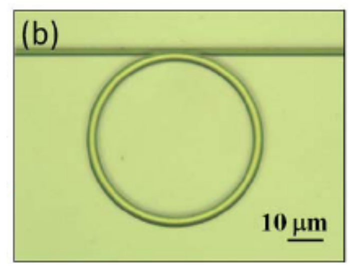
silicon

Griffith *et al.*, (2014).



Si nitride

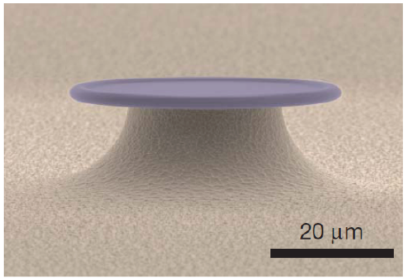
Levy *et al.*, Nat. Photon. (2010).
Ferdous *et al.*, Nat Photon. (2012).
Herr *et al.*, Nat. Photon. (2012).



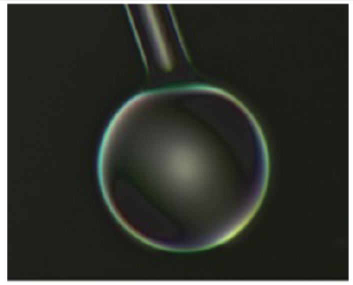
Al nitride

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

Microresonator-Based Parametric Combs



silica μ-toroids
Del' Haye *et al.*, Nature (2007).
Del' Haye *et al.*, PRL (2008).



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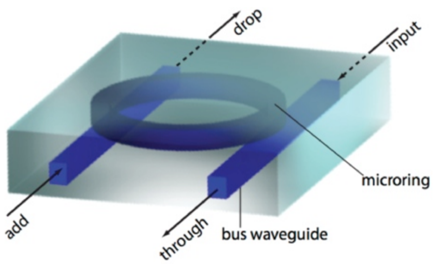
Papp & Diddams, PRA (2011).
Herr *et. al.*, Nat. Phot. (2012).



high-index glass μrings
Razzari *et al.*, Nature Photon. (2010).
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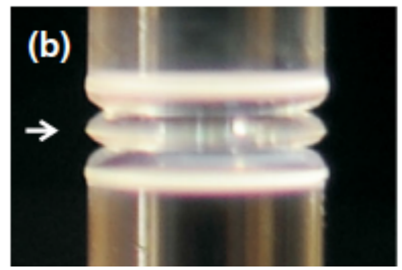
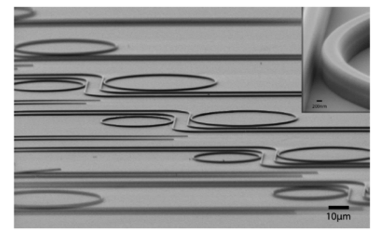
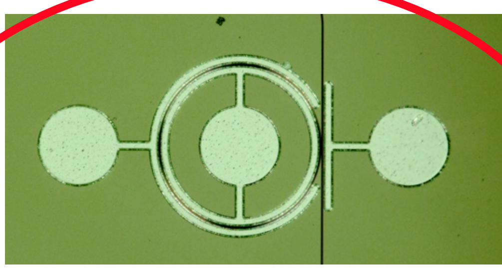


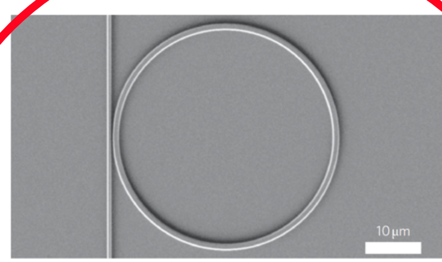
silica disks & rods
Li *et al.*, PRL (2012).
Papp, *et al.*, PRX (2013).



diamond
Hausmann *et al.*, Nat. Photon. (2013).



silicon
Griffith *et al.*, (2014).



Si nitride
Levy *et al.*, Nat. Photon. (2010).
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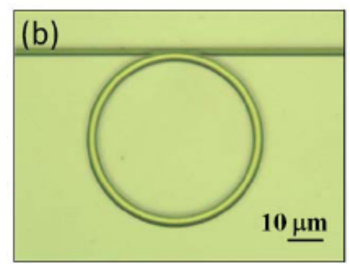
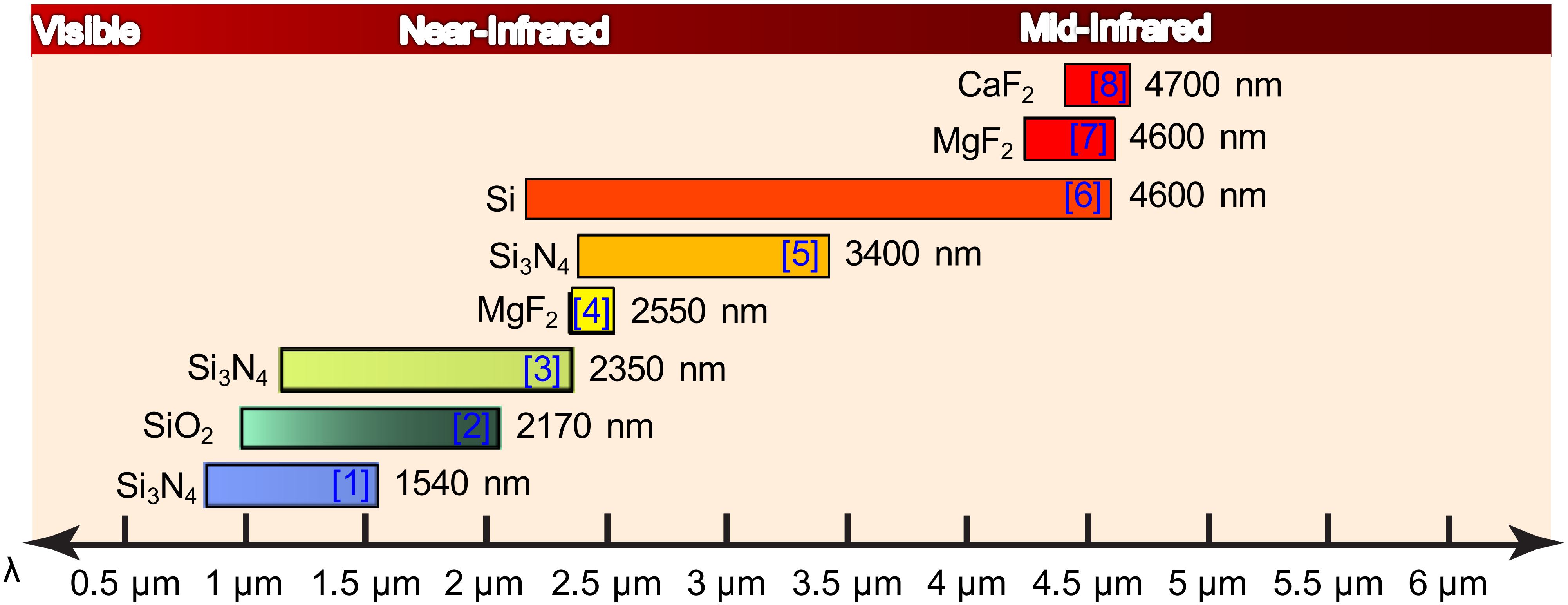
Herr *et al.*, Nat. Photon. (2012).



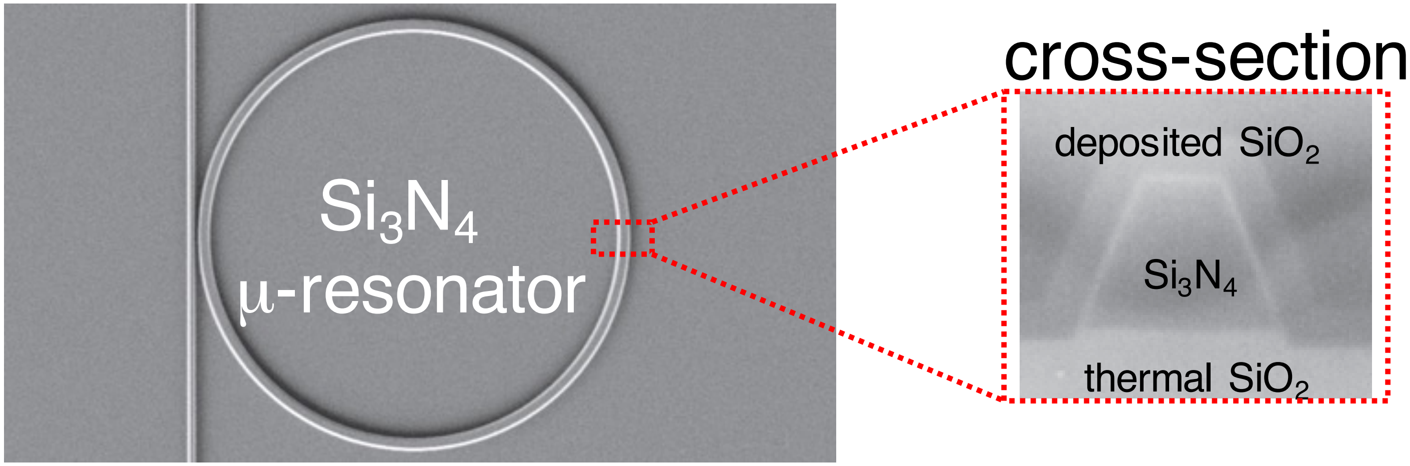
Al nitride
Jung *et al.*, Opt. Lett. (2013).

Microresonator Comb Spectral Coverage



[1] Saha, et al., Lipson & Gaeta (2013); Luke, *et al.*, Gaeta & Lipson, in preparation (2015).
[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] Griffiths, *et al.*, Gaeta & Lipson, Nat. Comm. (2015).
[6] Luke, *et al.*, Gaeta and Lipson, in preparation (2015).
[7] Lecaplain, et al., Kippenberg, arXiv (2015).
[8] Savchenko, et al., Maleki, arXiv (2015).

Silicon-Based Microresonators for Parametric Comb Generation



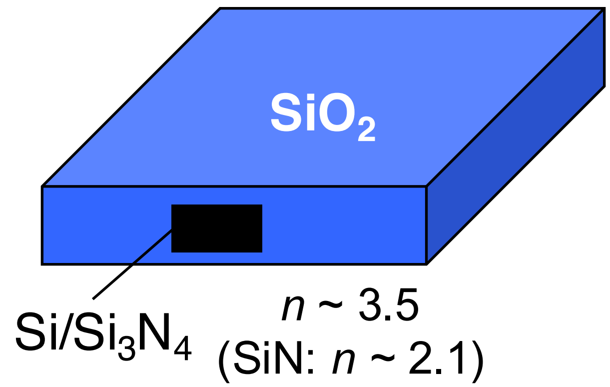
- CMOS-compatible material
- Fully monolithic and sealed structures and couplers
- High-Q resonators → Si_3N_4 $Q = 7 \times 10^6$ [Luke, et al., *Opt. Express* (2013).]

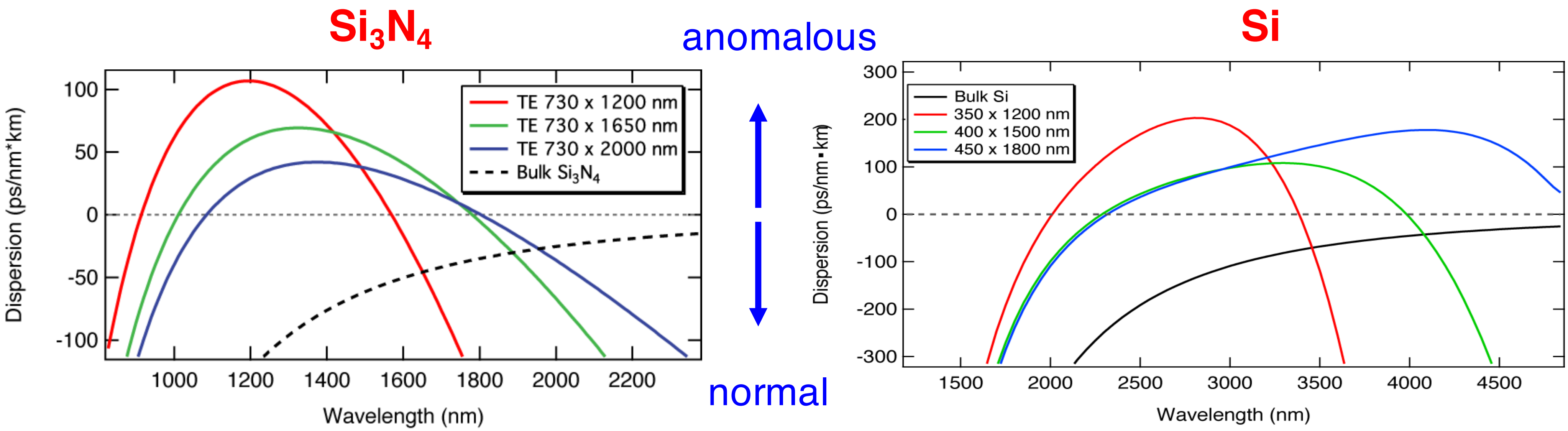
  Si $Q \sim 10^6$ [Lee, et al., (2013).]
- High nonlinearity → $n_2 \sim$ 10-100 × silica
- Waveguide dispersion can be engineered

[Foster, et al., Lipson, Gaeta, *Nature* **441**, 960 (2006).
Turner-Foster, et al., Gaeta, Lipson, *Opt. Express* **18**, 1904 (2010).]]

Tailoring of GVD in Si-Based Waveguides

- GVD can be tuned by varying waveguide shape and size.
- Same chip can operate w/ different pump wavelengths.

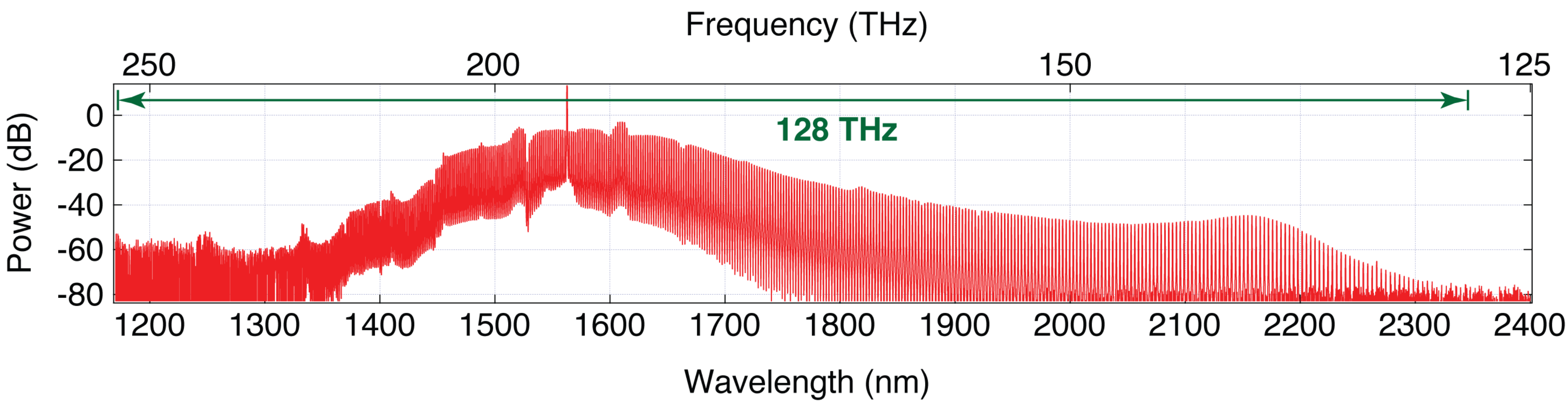




- Oxide cladding limits generation < 5 μm (?)

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

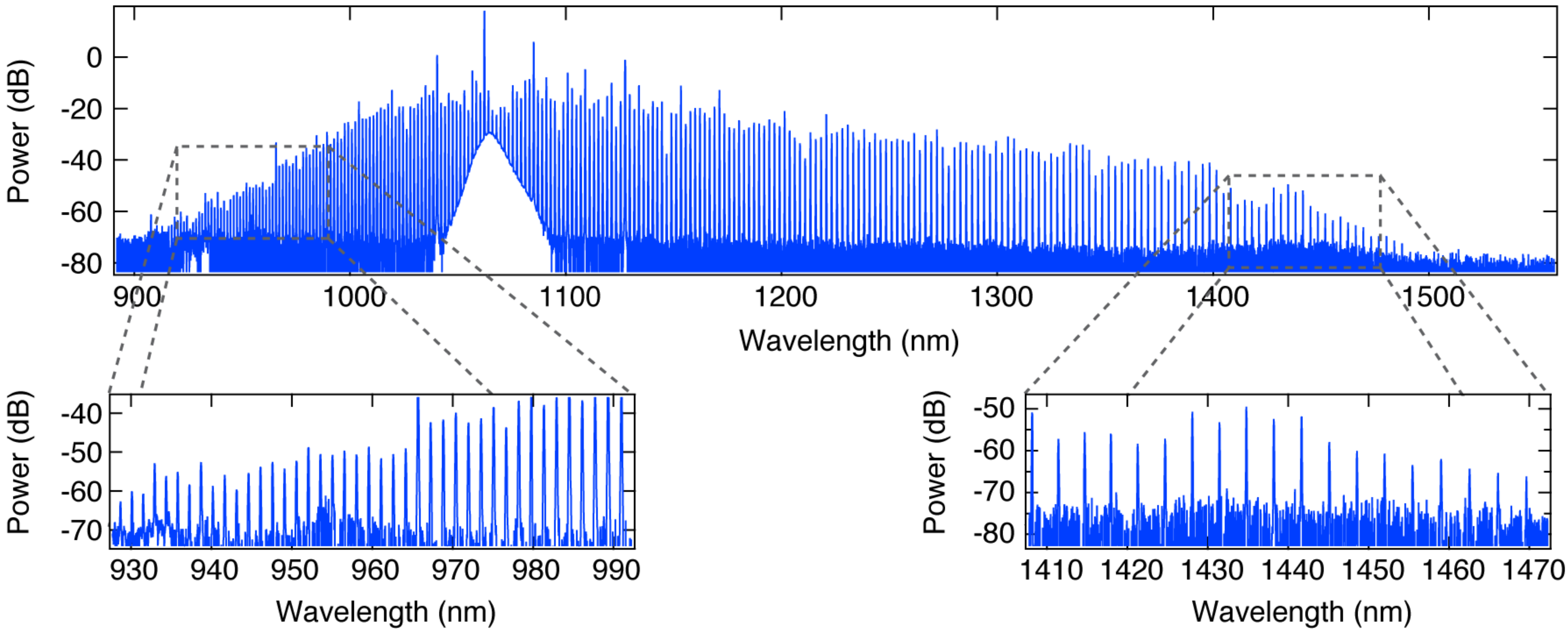
Octave-Spanning Comb in Si_3N_4



- > 150 THz bandwidth
- Stable, robust, highly compact comb source for clock applications
- Modest power requirements (100's of mW)

Okawachi, et al., Lipson, and Gaeta, *Opt. Lett.* (2011).

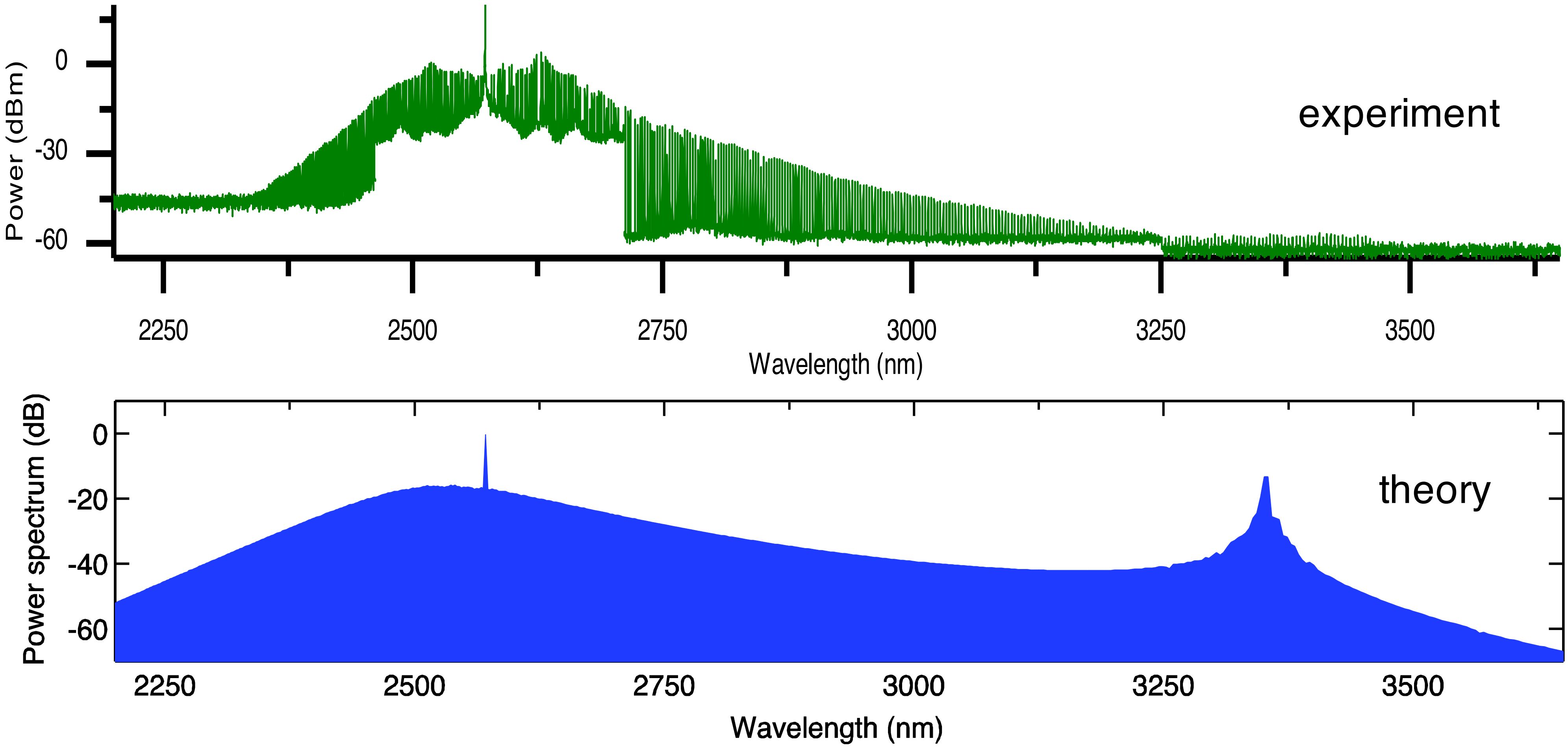
Dispersion Engineering: Broadband Combs with 1-μm Pump in Si_3N_4



- 690 x 1400 nm cross section, 46-μm resonator radius (500 GHz FSR)
- >2/3 octave of continuous comb bandwidth

Saha, et al., Lipson, and Gaeta, Opt. Express (2012)
Luke et al. Lipson, Gaeta, to be published (2014).

Mid-IR Comb in Si_3N_4



- 950 x 2700 nm waveguide
- Fully filled in comb spanning 2.3 - 3.4um
- P_{th} ~ 80 mW, FSR = 99GHz

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

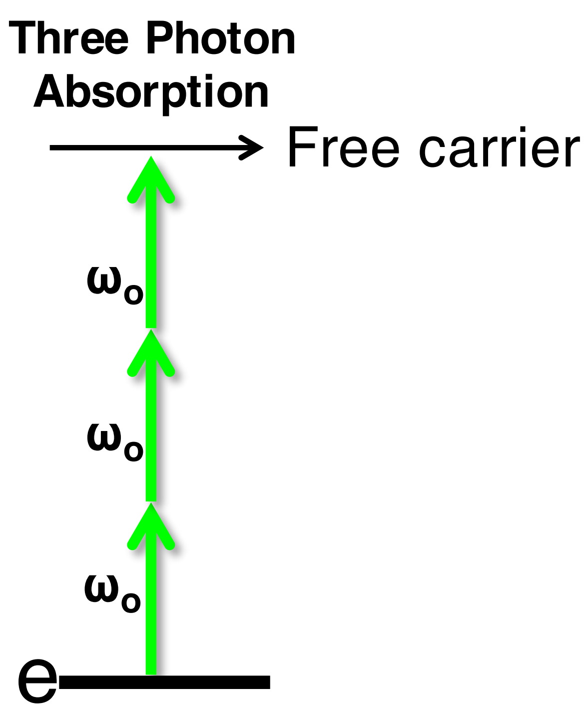
Silicon as a Mid-IR Material

Advantages:

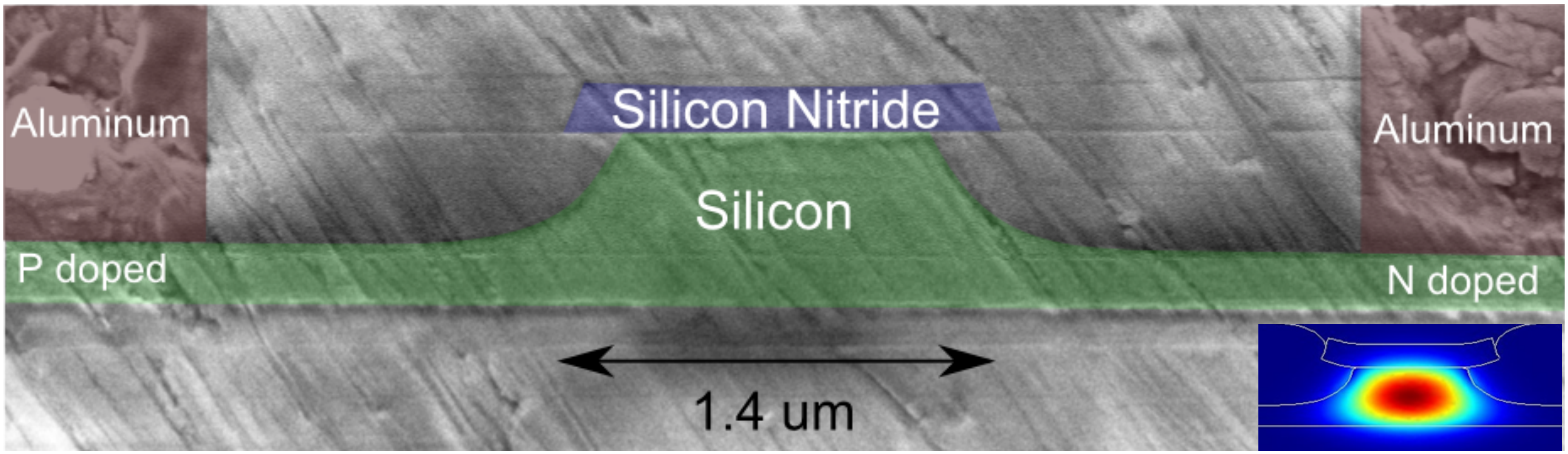
- Large 3rd order nonlinearity
- Transparent to ~ 8 um
- High refractive index

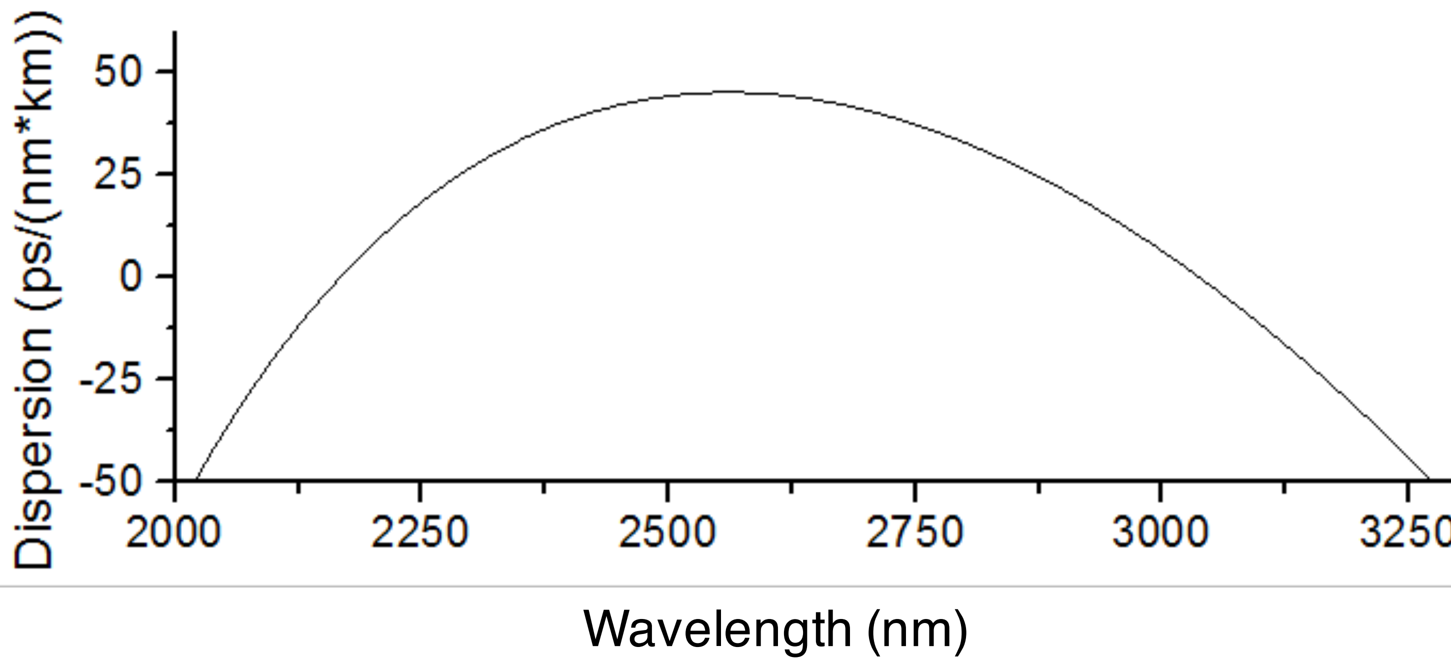
Problem:

- Need to pump > 2 μm
- Three-photon absorption
- Significant above 1 Watt circulating power



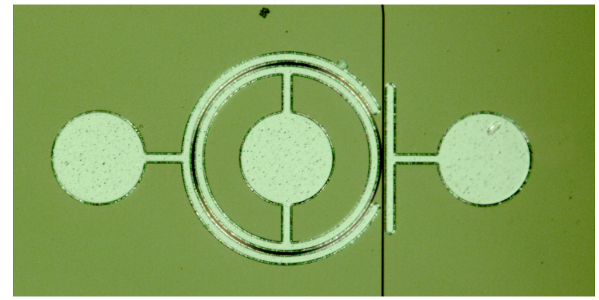
Fabricated Silicon Device



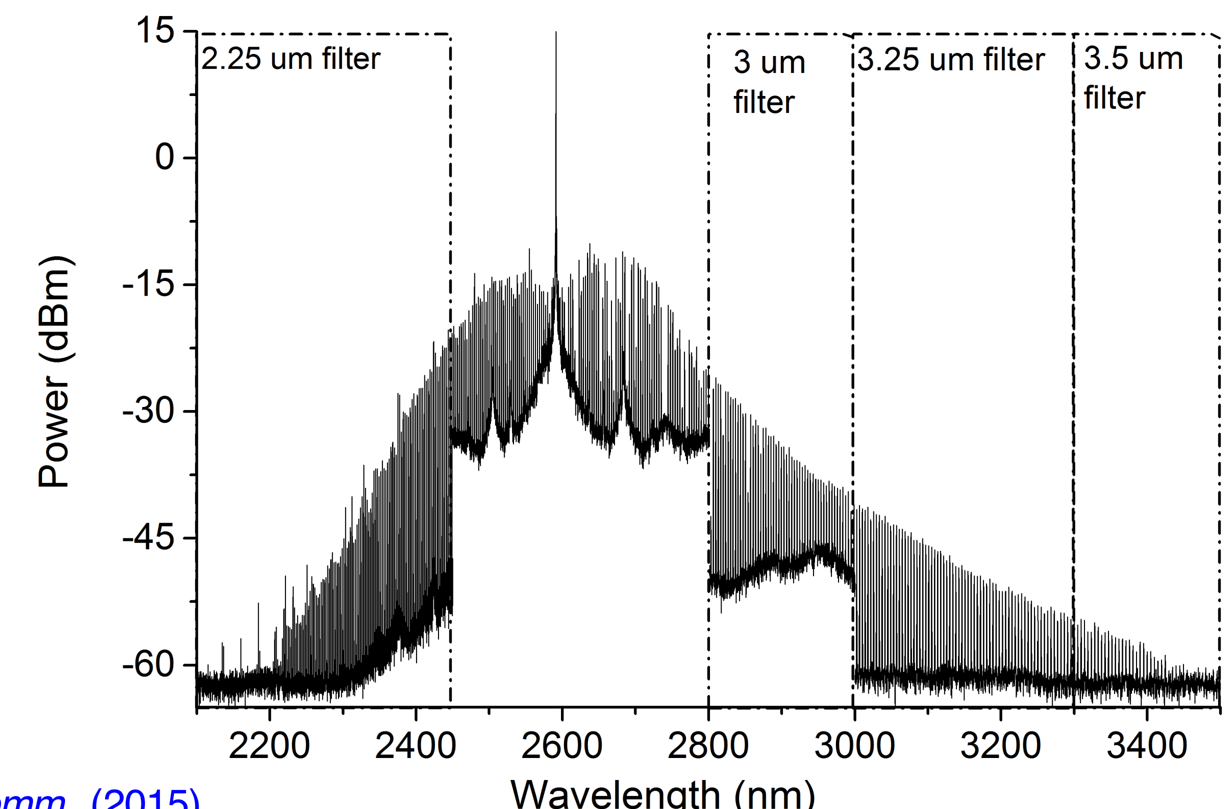


Mid-IR Parametric Frequency Comb

- 500 × 1400 nm **etchless silicon** microresonator with ***p-i-n* structure**
- Q-factor ~10^6
- Measurement with FTIR OSA
  ➔Bandwidth limited by dynamic range of OSA

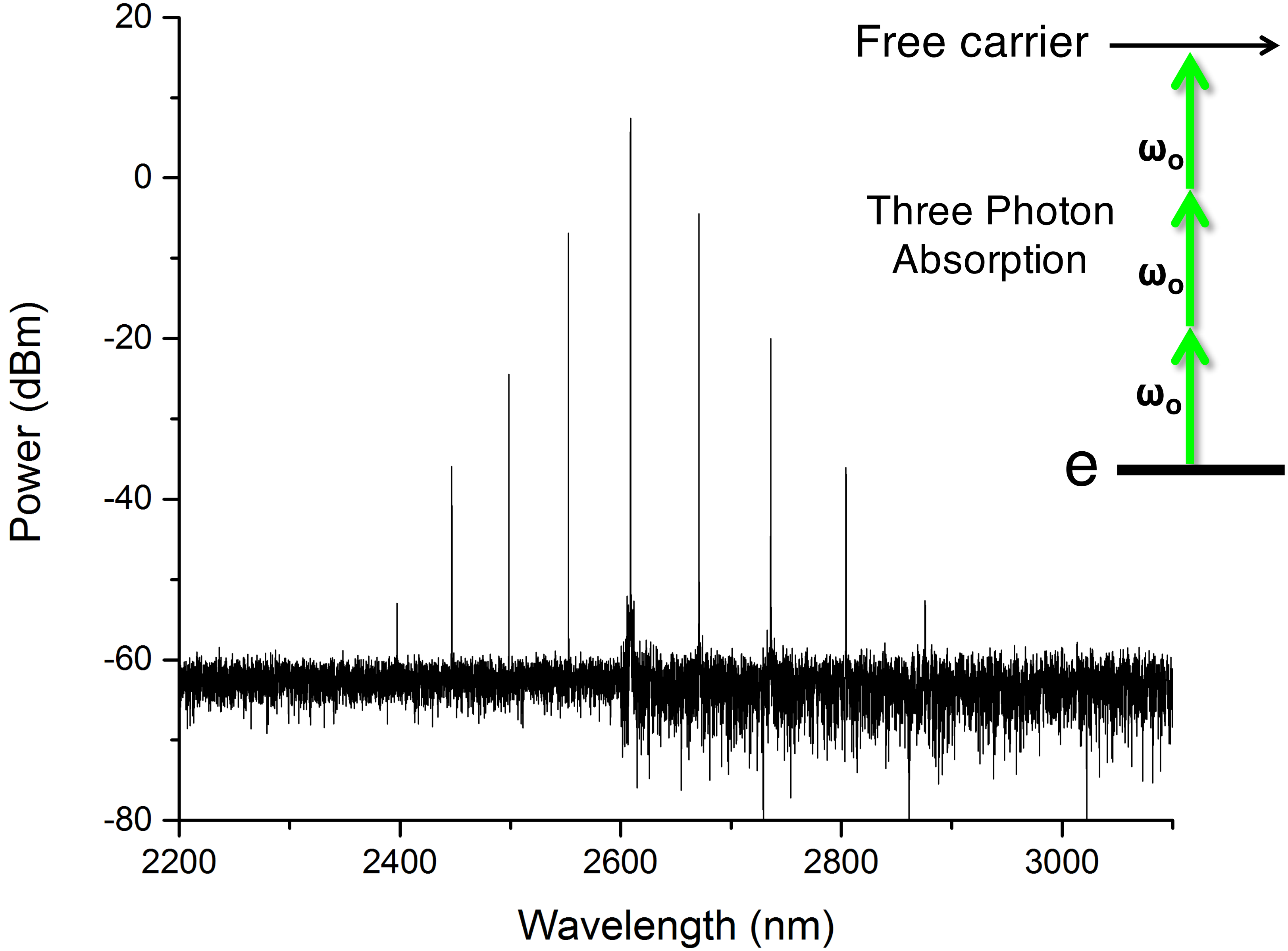


- 2608-nm pump
- 750-nm bandwidth
- 125-GHz FSR
  (100 μm radius)

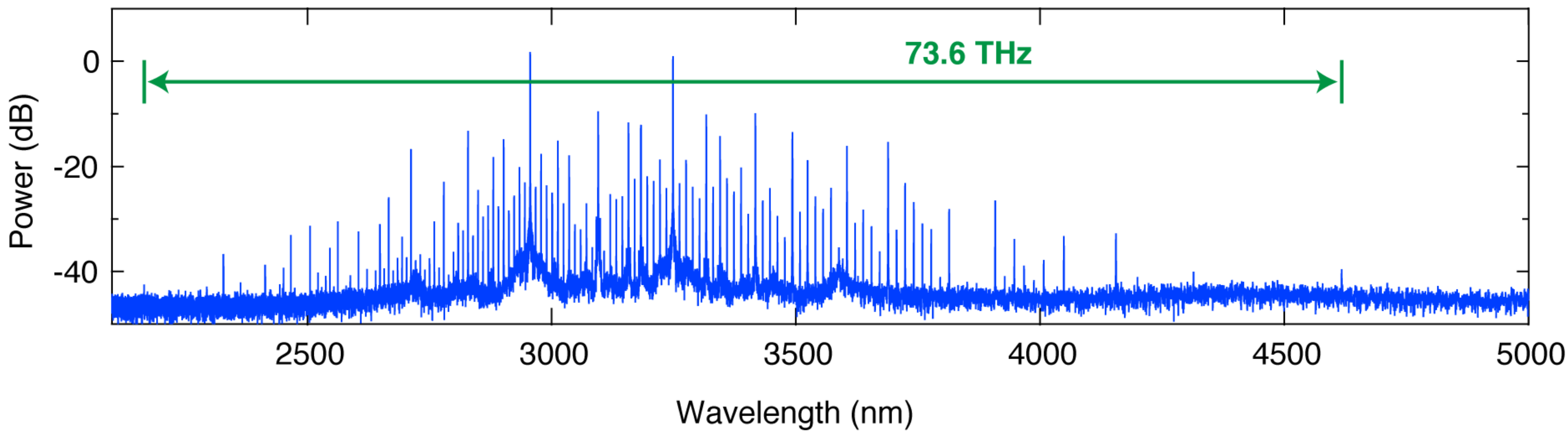


Griffith, et al., Gaeta and Lipson, *Nat. Comm.* (2015)

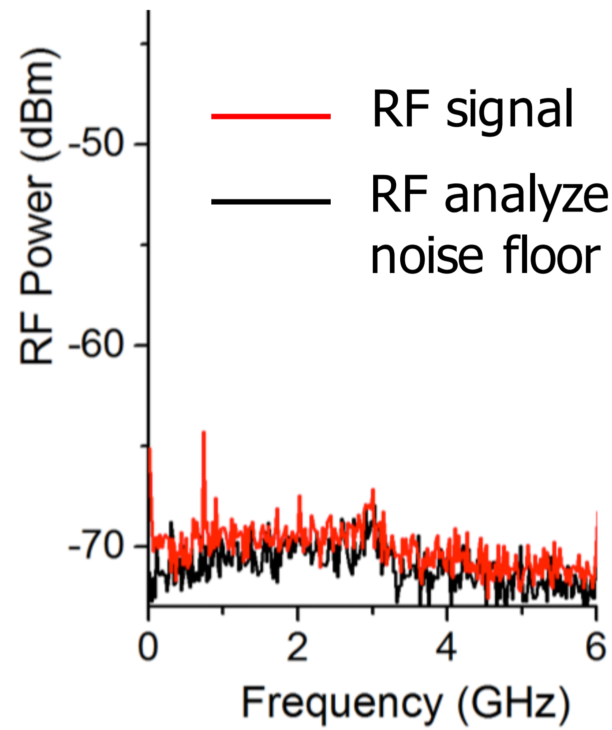
Comb Generation without Carrier Extraction



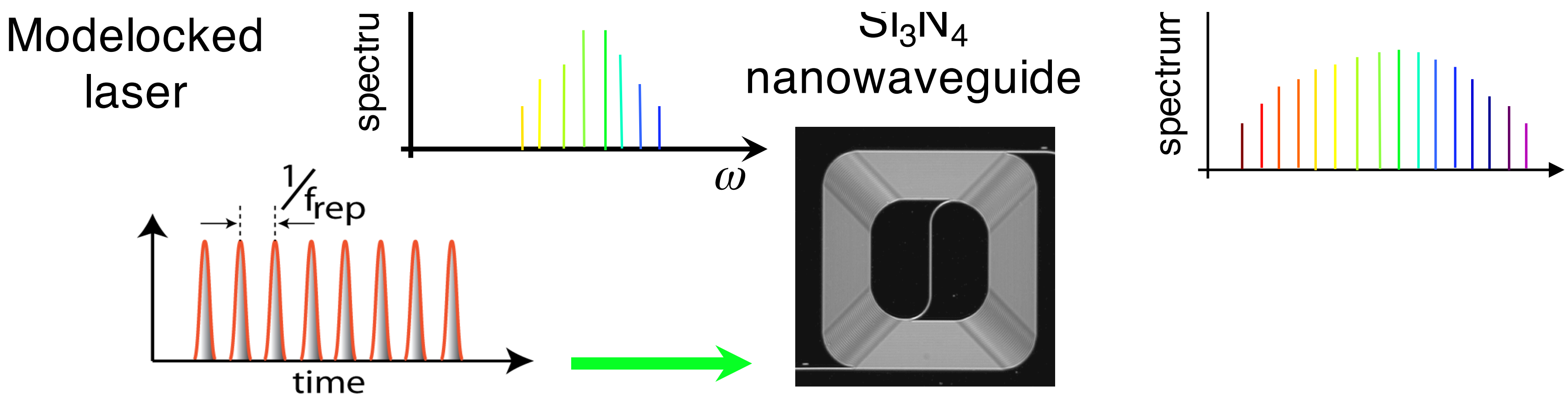
Near Octave-Spanning Mid-IR Comb Generation in Si Microresonator



- Pump wavelength 3095 nm
- Comb spans > octave
- Wavelength range: 2165 – 4617 nm
- Comb exhibits low RF noise



Chip-Based Comb Generation

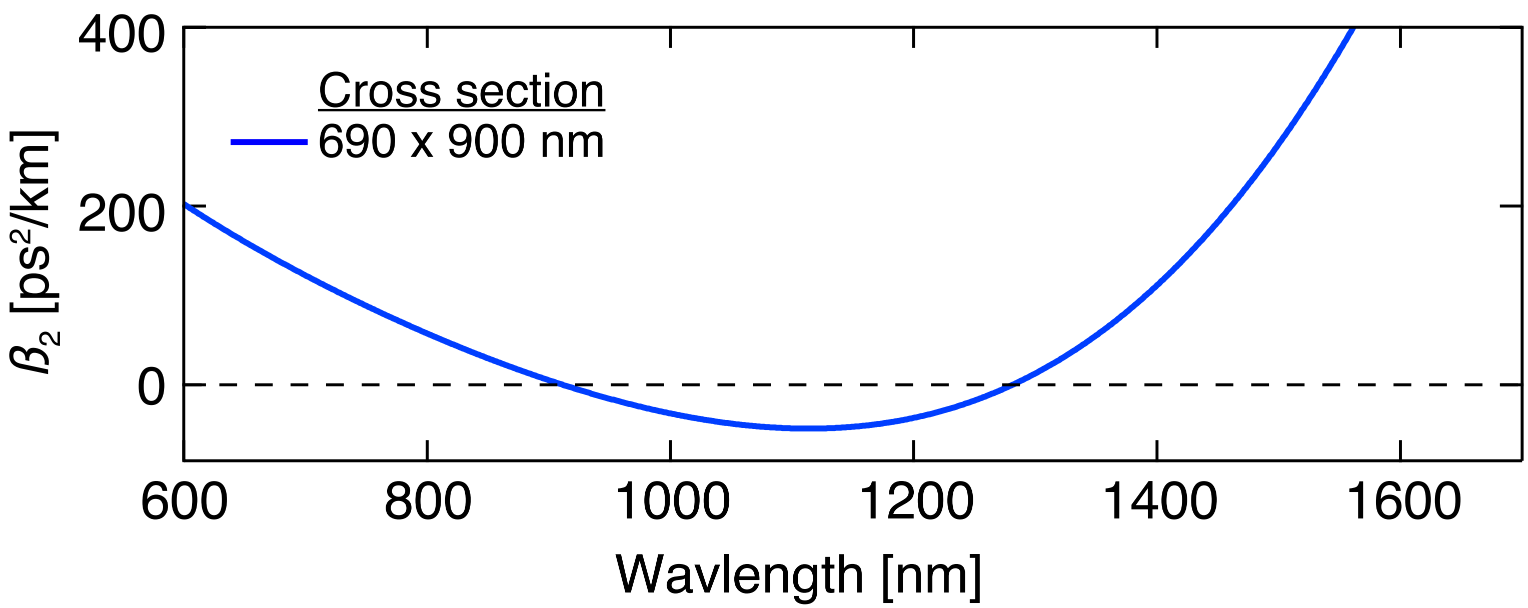


- Origin of combs can be traced to ***four-wave mixing (FWM)***
- Requires small anomalous group-velocity dispersion

Waveguide Design for Octave-Spanning Coherent SCG at 1 μm

Quantum & Nonlinear Optics Group
Columbia University

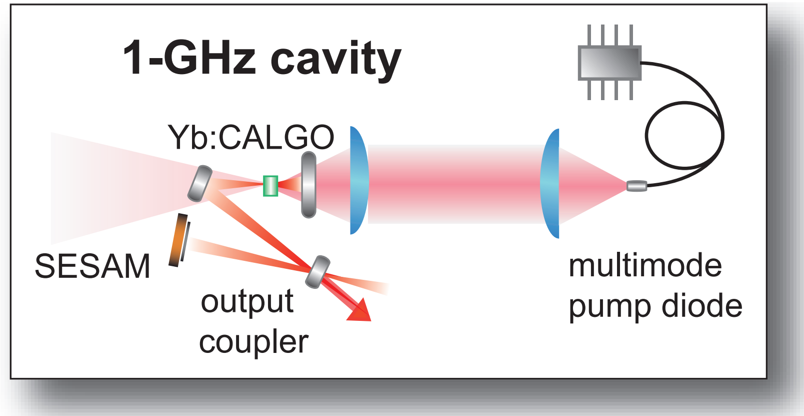
- Engineer dispersion by tailoring waveguide cross section
- Design broad region of anomalous group velocity dispersion (β_2) around 1-μm pump
- Coherent SCG with 100-fs pump through self-phase modulation and dispersive wave emission

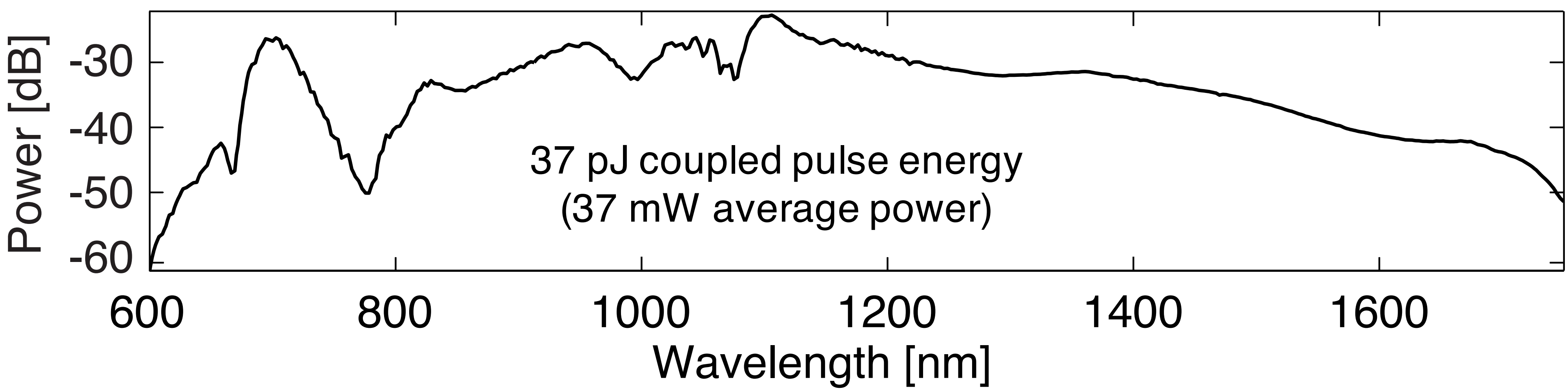


Supercontinuum Generation with Diode-Pumped Solid-State Laser

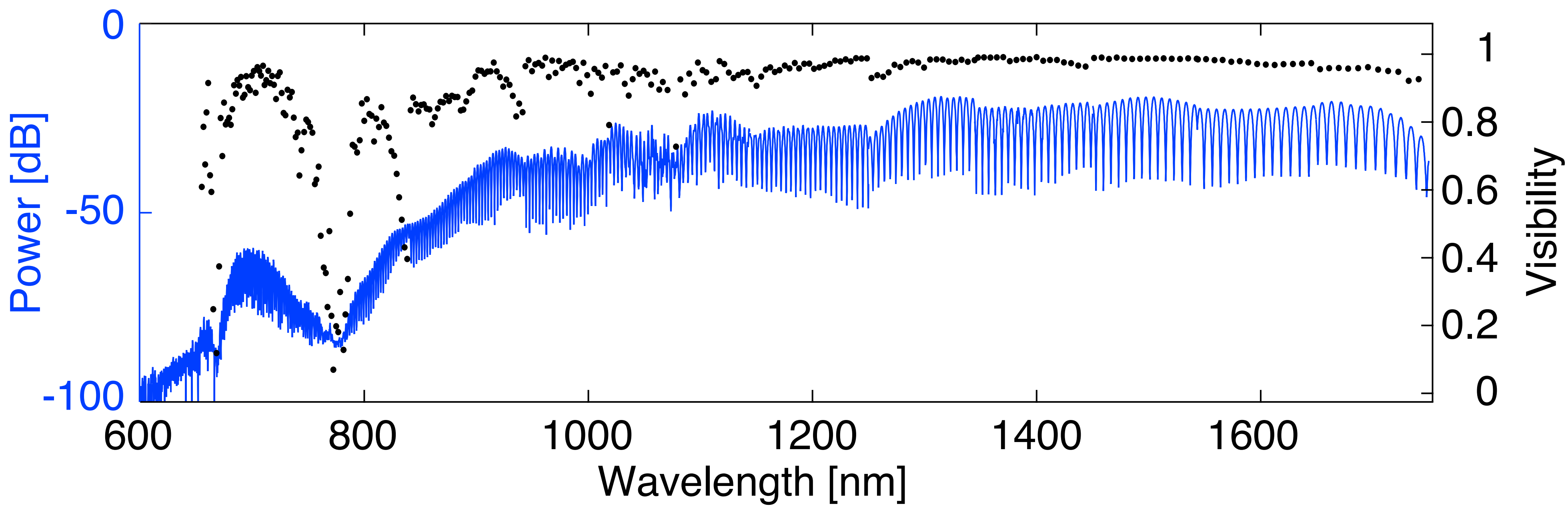
Collaboration w/ Ursula Keller's group (ETH-Zurich)

- Pump with 1-GHz repetition rate SESAM-modelocked diode-pumped Yb:CALGO laser [Klenner *et al.*, Opt. Express (2014)]
- 92-fs input pulses, 1055 nm center wavelength





Supercontinuum Coherence Measurement



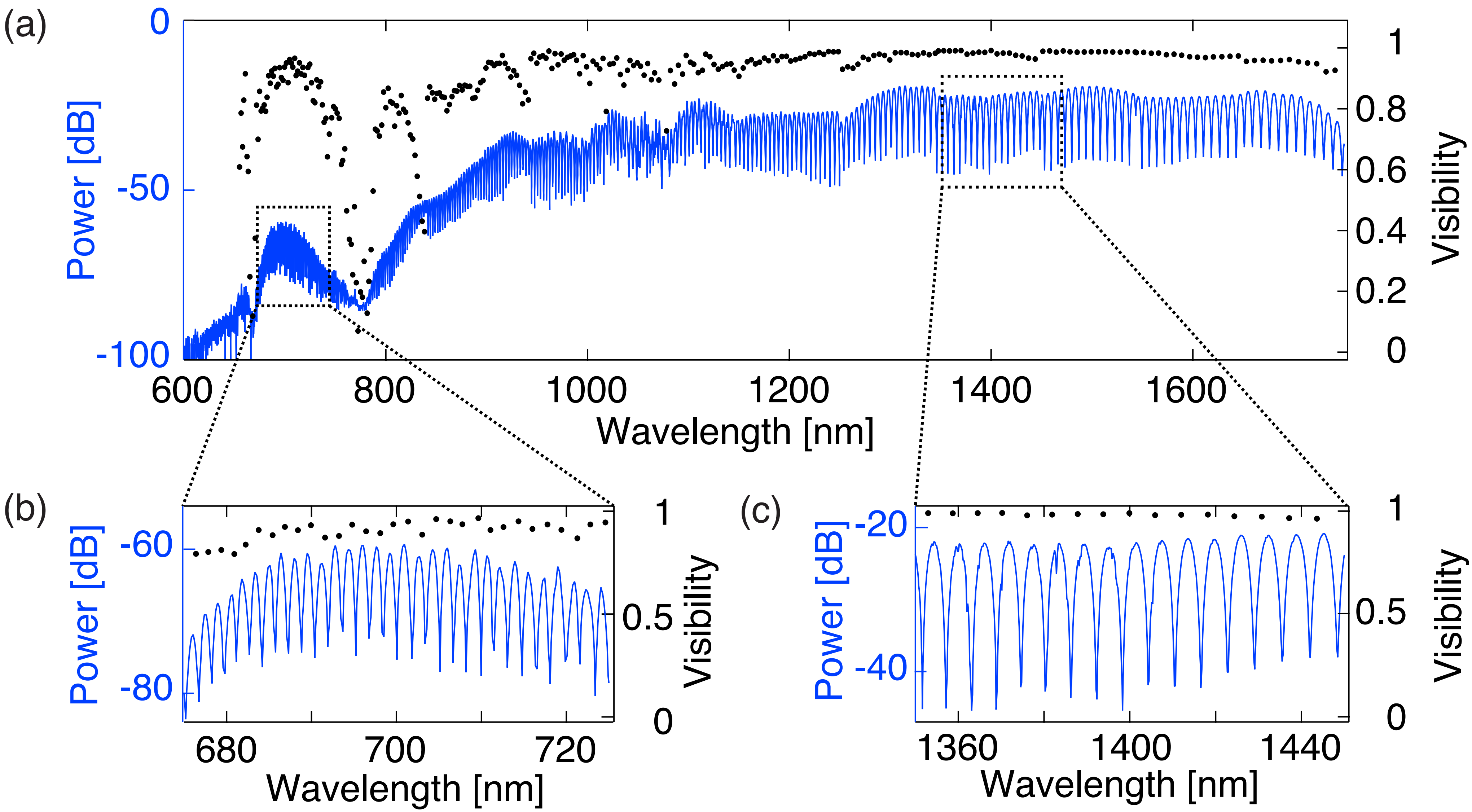
- OSA sweep records ensemble average
- Coherence $\left|g_{12}^{(1)}\right|$ related to visibility $V(\lambda)$

[Nicholson and Yan, Opt. Express (2004); Gu *et al.*, Opt. Express (2011)]

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

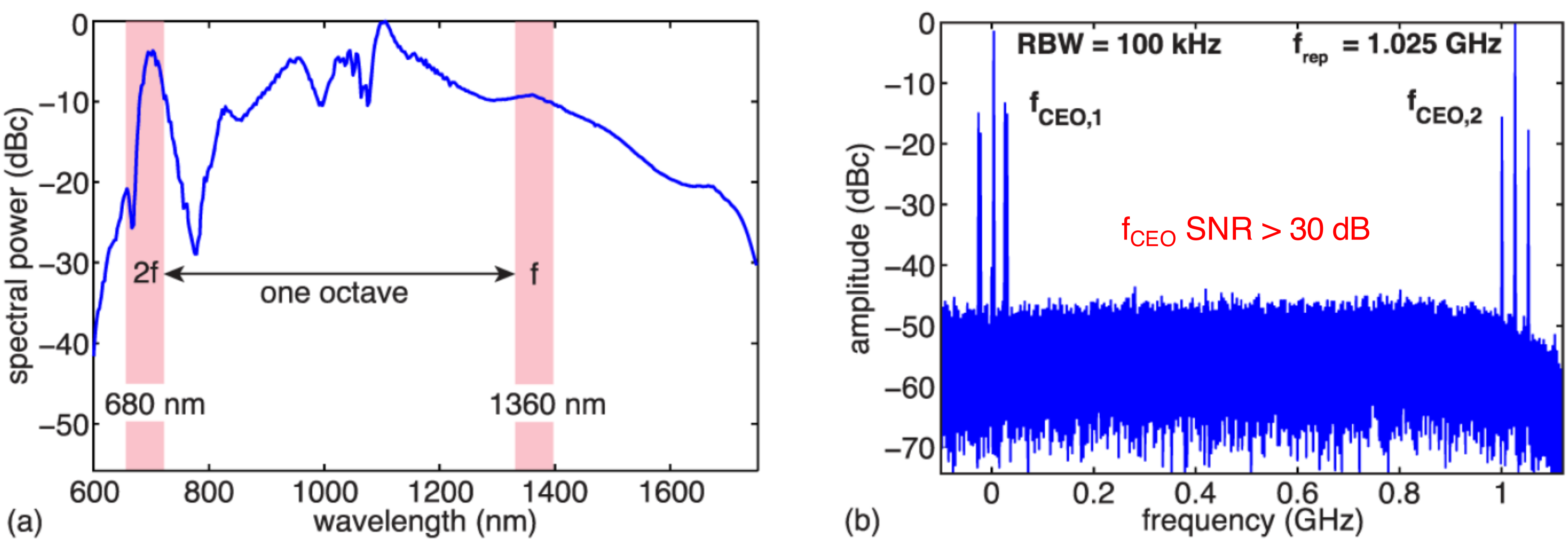
- Perform coherence measurement in 100-nm increments

Coherent Supercontinuum for f-to-2f Interferometry



Carrier Envelope Offset Frequency Detection Using Silicon Nitride Waveguide

- Carrier envelop offset frequency (f_{ceo}) beatnote from *f*-to-2*f* interferometry
- Spectrum at 1360 nm is frequency doubled and overlapped with spectrum at 680 nm
- f_{ceo} signal-to-noise ratio > 30 dB
- Much lower noise level (10 dB) than w/ PCF

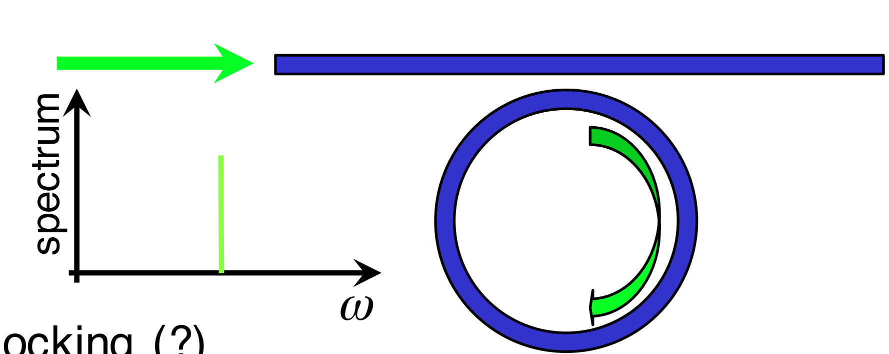


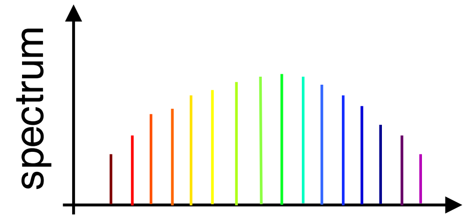
[Mayer *et al*., Opt. Express (2015)]

Comparison of Comb Generation Schemes

Pump Properties

- single-frequency
- P > 200 mW
- CEO control
- Tuning for modelocking (?)





Microresonator Properties

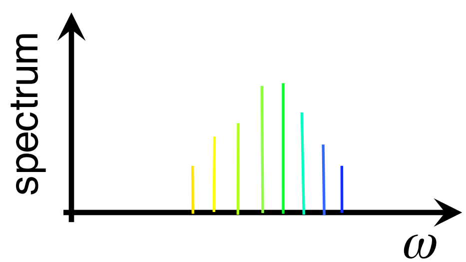
- Thermal issues important
- Comb spacing control (thermal)
- Modelocking (Thermal?)

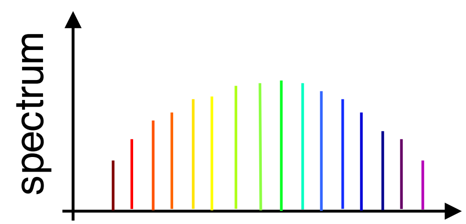
Comb Properties

- Spacing > 20 GHz
- > 200 μW/line
- Stabilized ~ 2/3 Octave
- Near-IR – mid-IR

Pump Properties

- Modelocked
- < 200 fs for coherent comb
- CEO & comb spacing control
- P ~ 40 mW





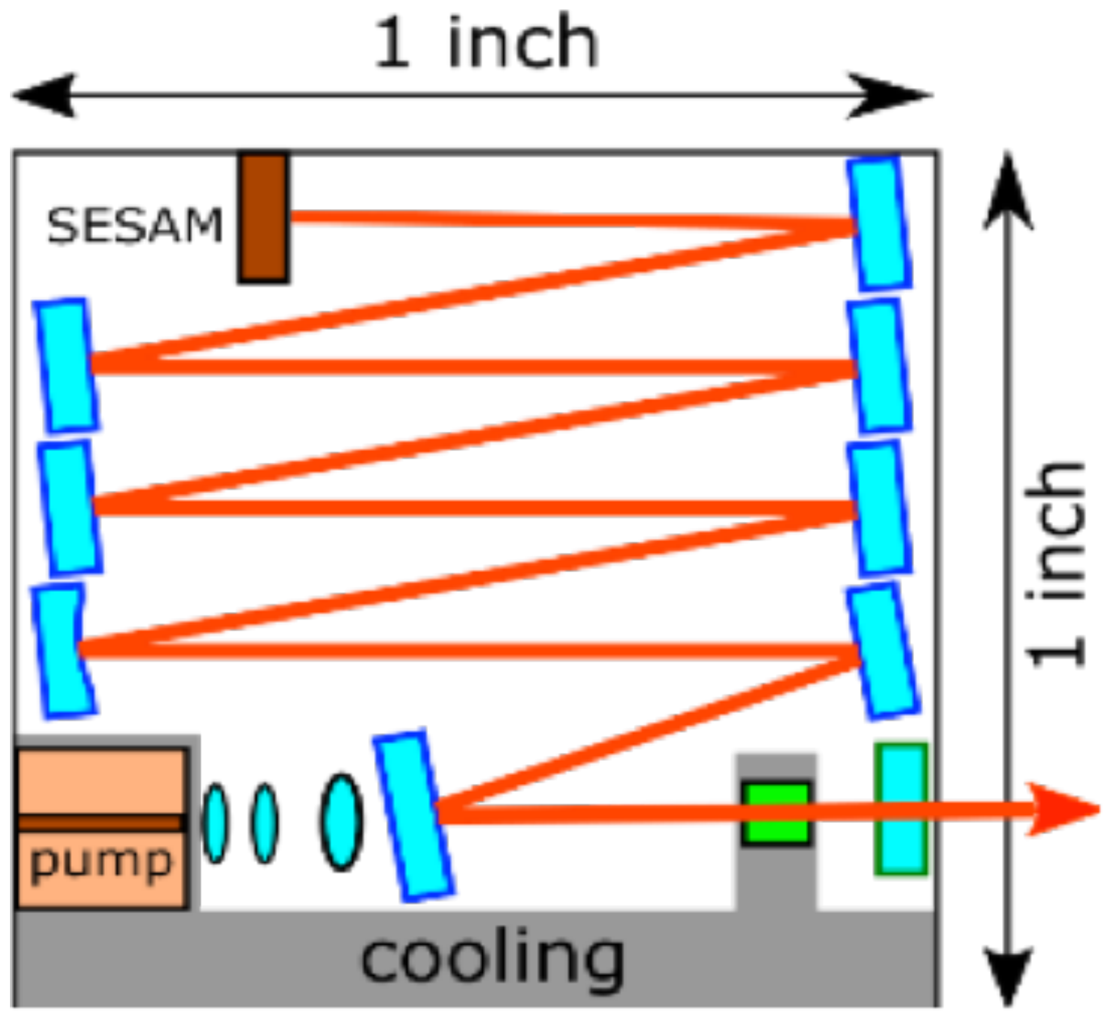
Nanowaveguide Properties

- Passive
- Waveguide dispersion tailored longitudinally

Comb Properties

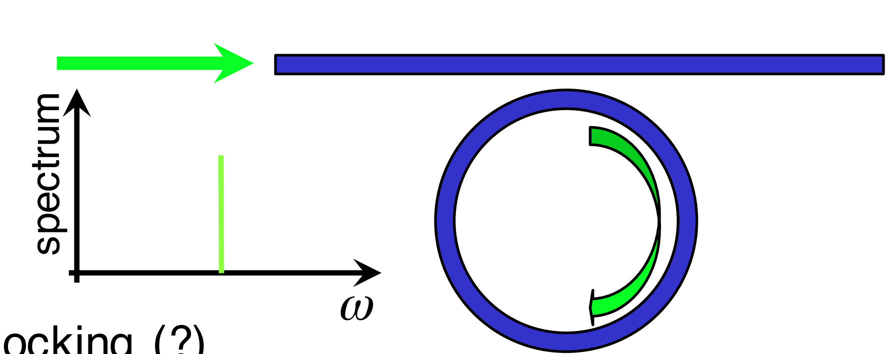
- Spacing > 20 GHz
- > 100 nW/line
- Stabilized > Octave
- Visible – mid-IR

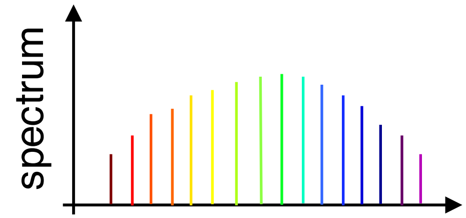
Compact Solid-State 5-GHz Modelocked Laser



Comparison of Comb Generation Schemes

Pump Properties
- single-frequency
- P > 200 mW
- CEO control
- Tuning for modelocking (?)

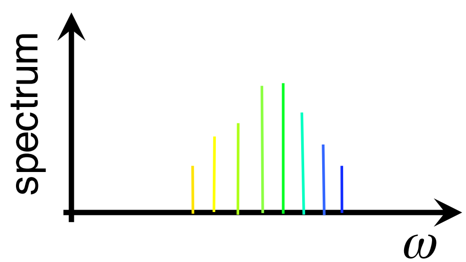


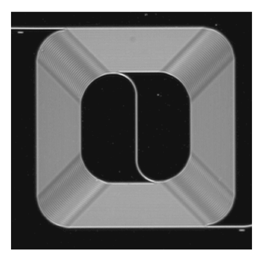


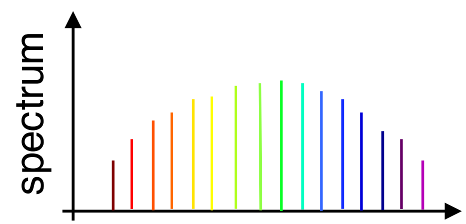
Comb Properties
- Spacing > 20 GHz
- 1 - 200 μW line
- Stabilized ~ 2/3 Octave
- Near-IR – mid-IR

Microresonator Properties
- Thermal issues important
- Comb spacing control (thermal)
- Modelocking (Thermal?)

Pump Properties
- Modelocked
- < 200 fs for coherent comb
- CEO & comb spacing control
- P ~ 40 mW





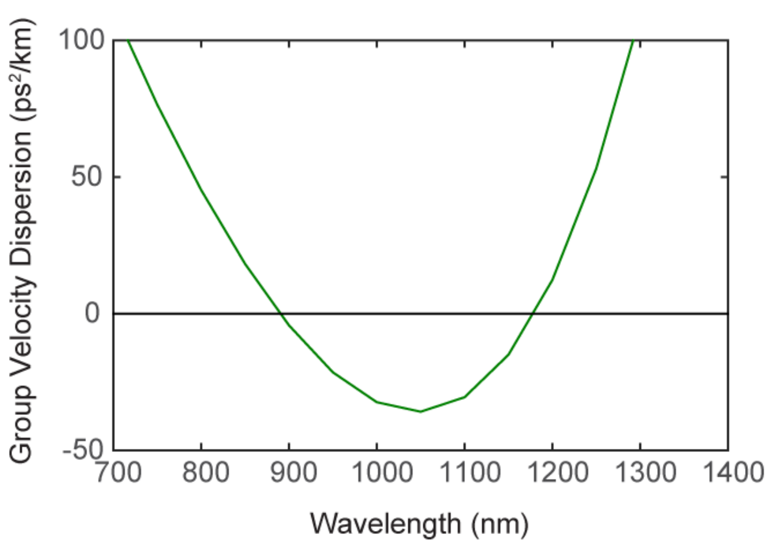


Comb Properties
- Spacing > 20 GHz
- 1 - 200 μW line
- Stabilized > Octave
- Visible – mid-IR

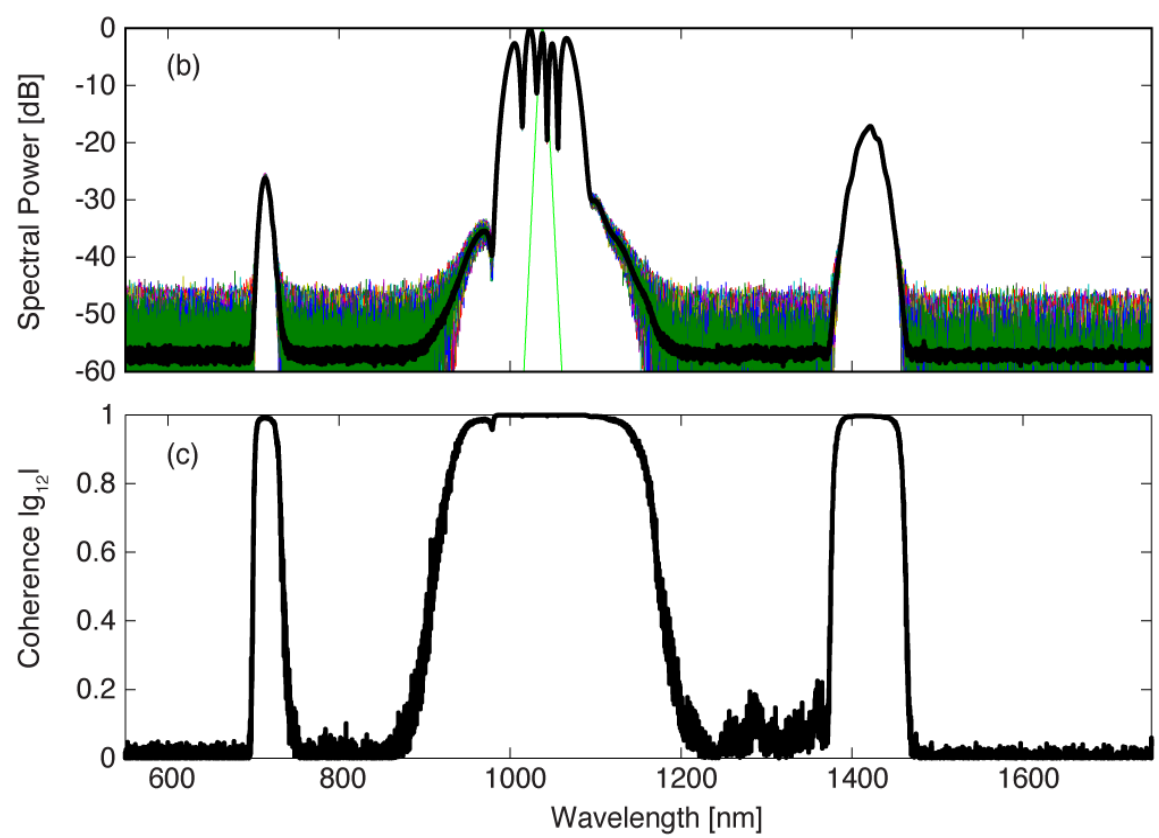
Nanowaveguide Properties
- Passive
- Waveguide dispersion tailored longitudinally

Spectrally Efficient Octave-Spanning Spectrum

- For applications (e.g., frequency synthesizer) that are particularly power sensitive.



Simulations

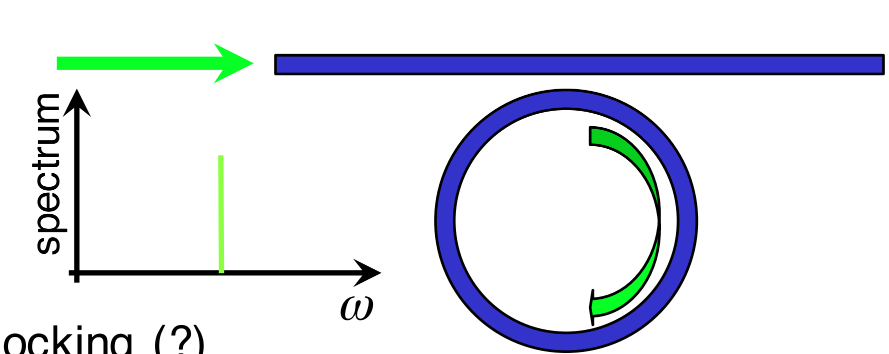


[Okawachi *et al.* Lipson & Gaeta (2015)]

Comparison of Comb Generation Schemes

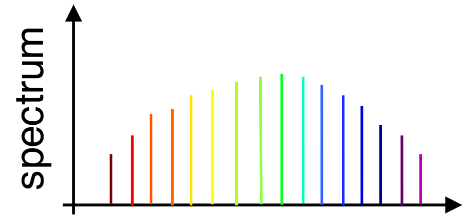
Pump Properties

- single-frequency
- P > 200 mW
- CEO control
- Tuning for modelocking (?)



Microresonator Properties

- Thermal issues important
- Comb spacing control (thermal)
- Modelocking (Thermal?)

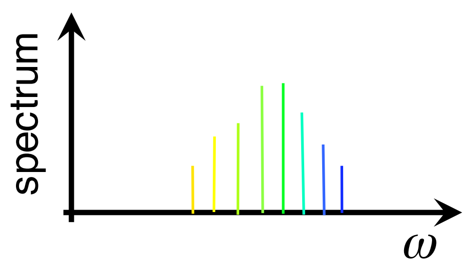


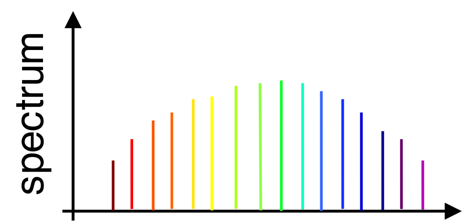
Comb Properties

- Spacing > 20 GHz
- 1 - 200 μW line
- Stabilized ~ 2/3 Octave
- Near-IR – mid-IR

Pump Properties

- Modelocked
- < 200 fs for coherent comb
- CEO & comb spacing control
- P ~ 40 mW





Nanowaveguide Properties

- Passive
- Waveguide dispersion tailored longitudinally

Comb Properties

- Spacing > 20 GHz
- 1 - 200 μW line
- Stabilized > Octave
- Visible – mid-IR