Generation of Mid-infrared Frequency Combs on a Silicon Chip

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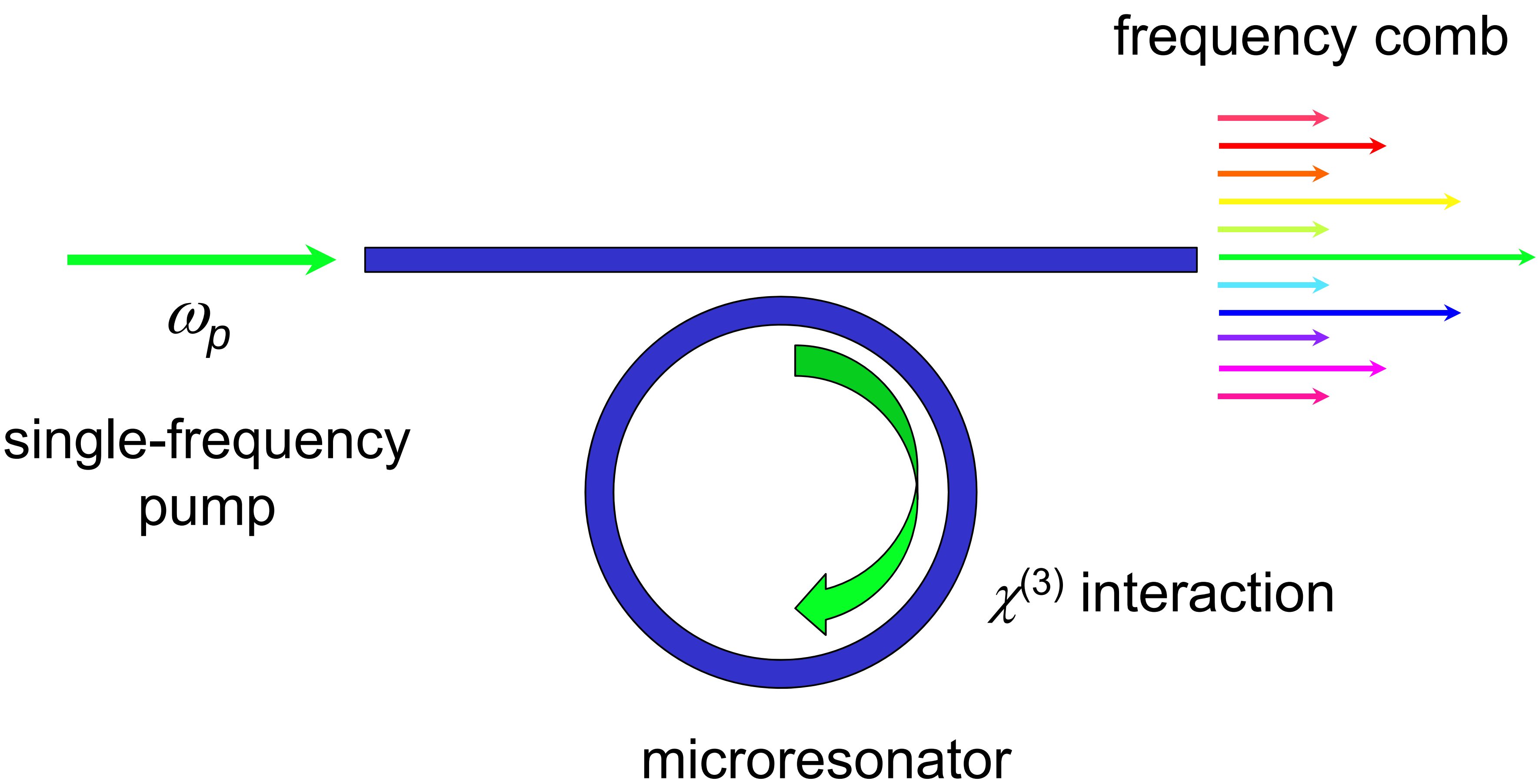
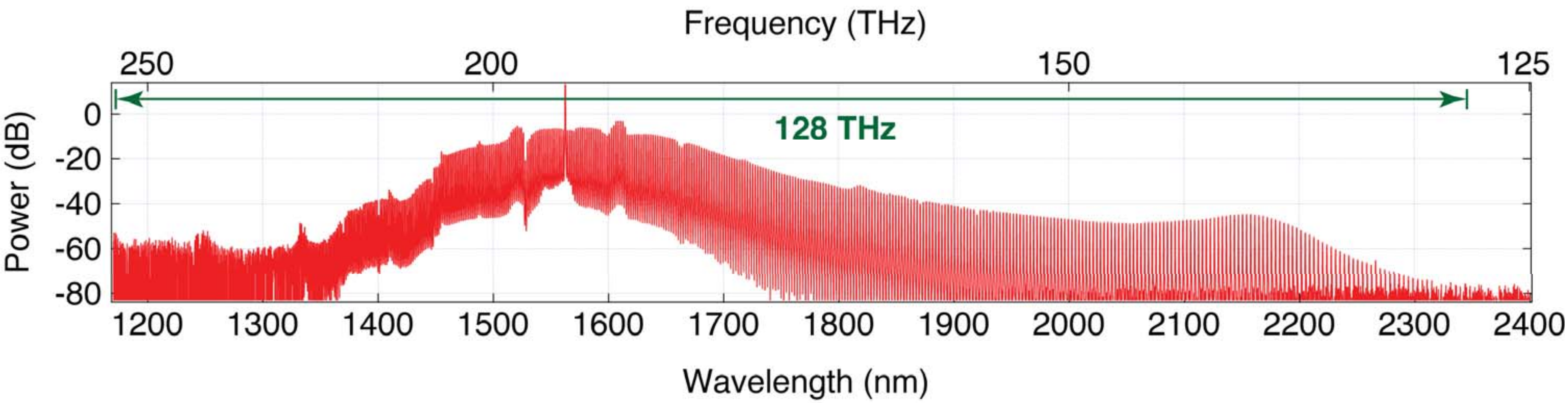
Comb Generation via Parametric Four-Wave Mixing Oscillation in Microresonators



Octave-Spanning Combs in Near Infrared in Si_3N_4



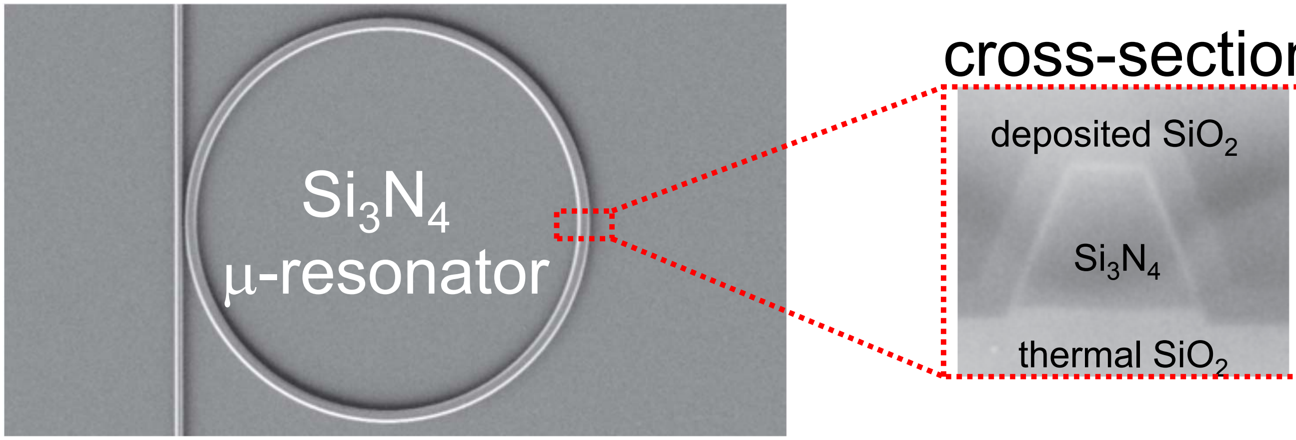
Okawachi, et al. Lipson & Gaeta, *Opt. Lett.* (2011).

- Si_3N_4 platform
- Stable, robust, highly compact.
- Modest power requirements (~ 400 mW).

Chip-scale comb source: 10 – 1000 GHz comb spacing

0.8 – 8 μm wavelength range

Silicon-Based Microresonators for Parametric Comb Generation



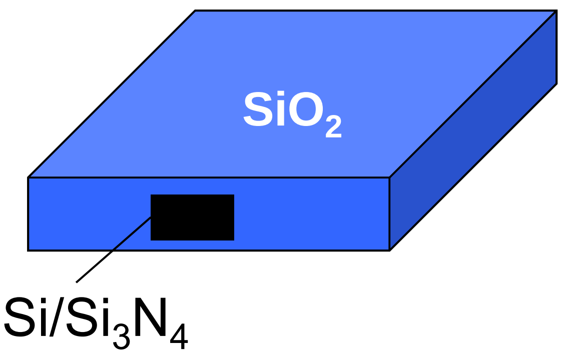
- CMOS-compatible material
- Fully monolithic and sealed structures and couplers
- High-Q resonators → Si_3N_4 $Q = 7 \times 10^6$ [Luke, et al., *Opt. Express* (2013).]

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

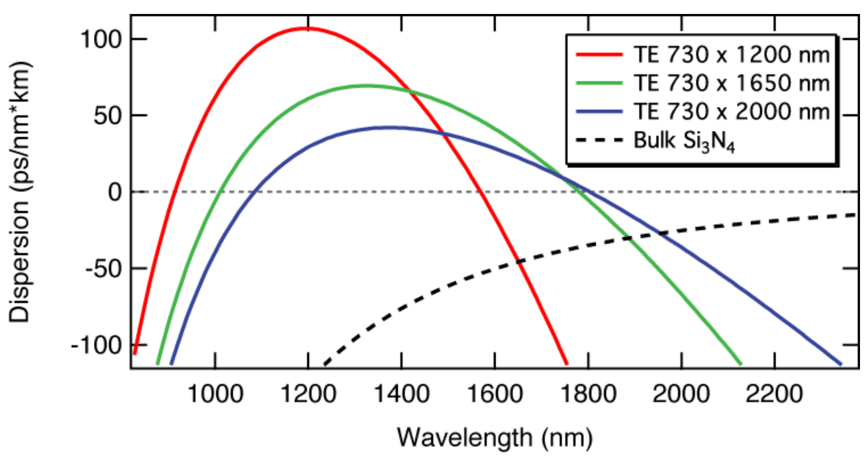
[Foster, et al., Lipson, Gaeta, *Nature* **441**, 960 (2006).
Turner-Foster, et al., Gaeta, Lipson, *Opt. Express* **18**, 1904 (2010).]

Tailoring of Dispersion in Si-Based Waveguides

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



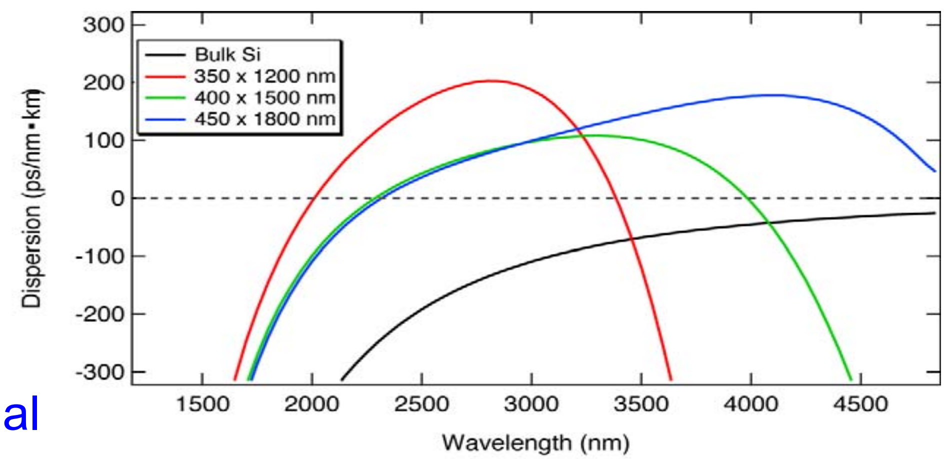
Si_3N_4



anomalous

normal

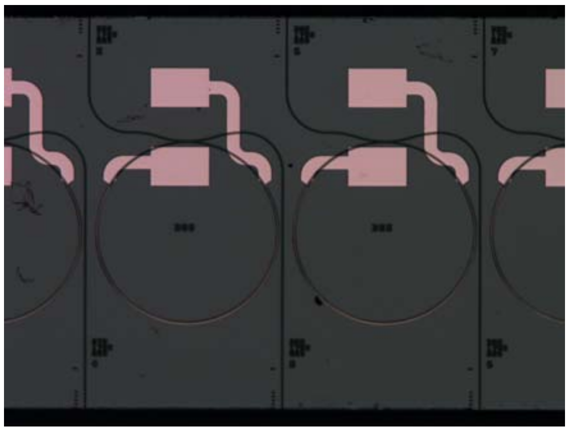
Si

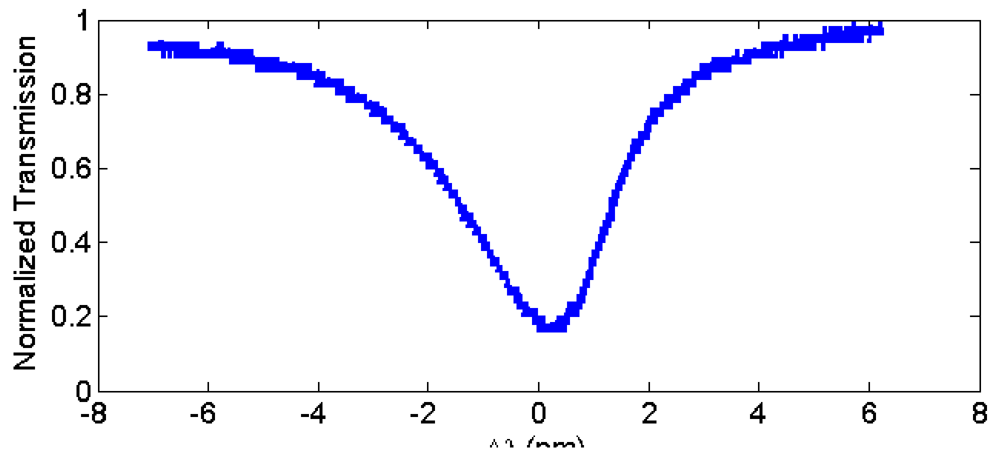


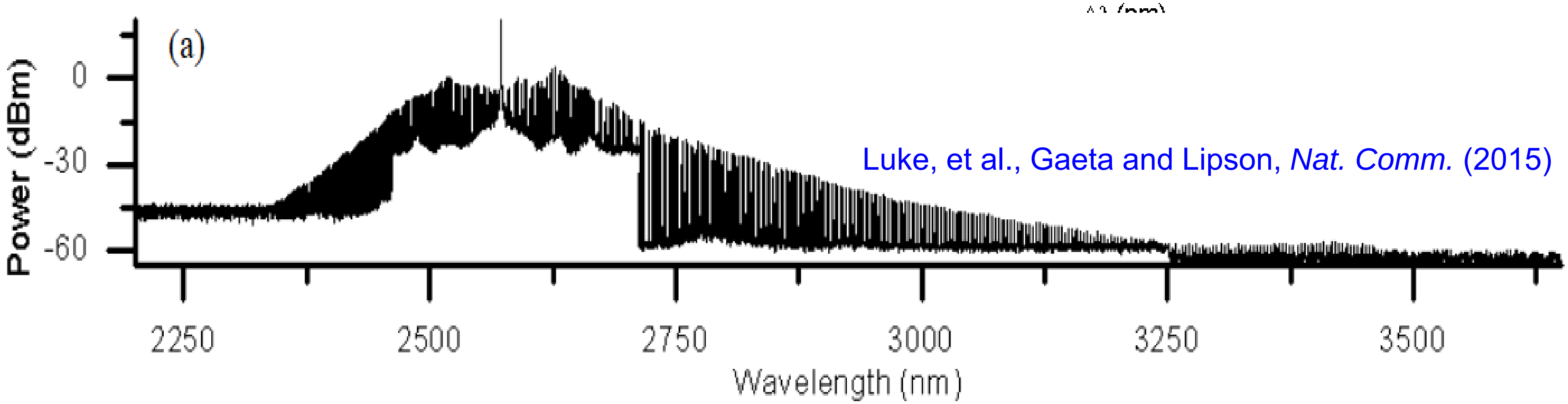
Foster, Turner, Sharping, Schmidt, Lipson, and Gaeta, *Nature* **441**, 960 (2006).
Turner, et al. Gaeta, and Lipson, *Opt. Express* **14**, 4357 (2006).

Mid-IR Parametric Frequency Comb in Si_3N_4 Microresonators

- Used improved fabrication process (DSP substrates, anneal mid-deposition, anneal cladding oxide)
- Demonstrated record Q of **1 million** at λ = 2.6 μm



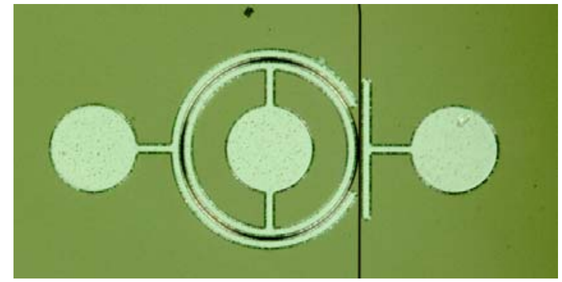




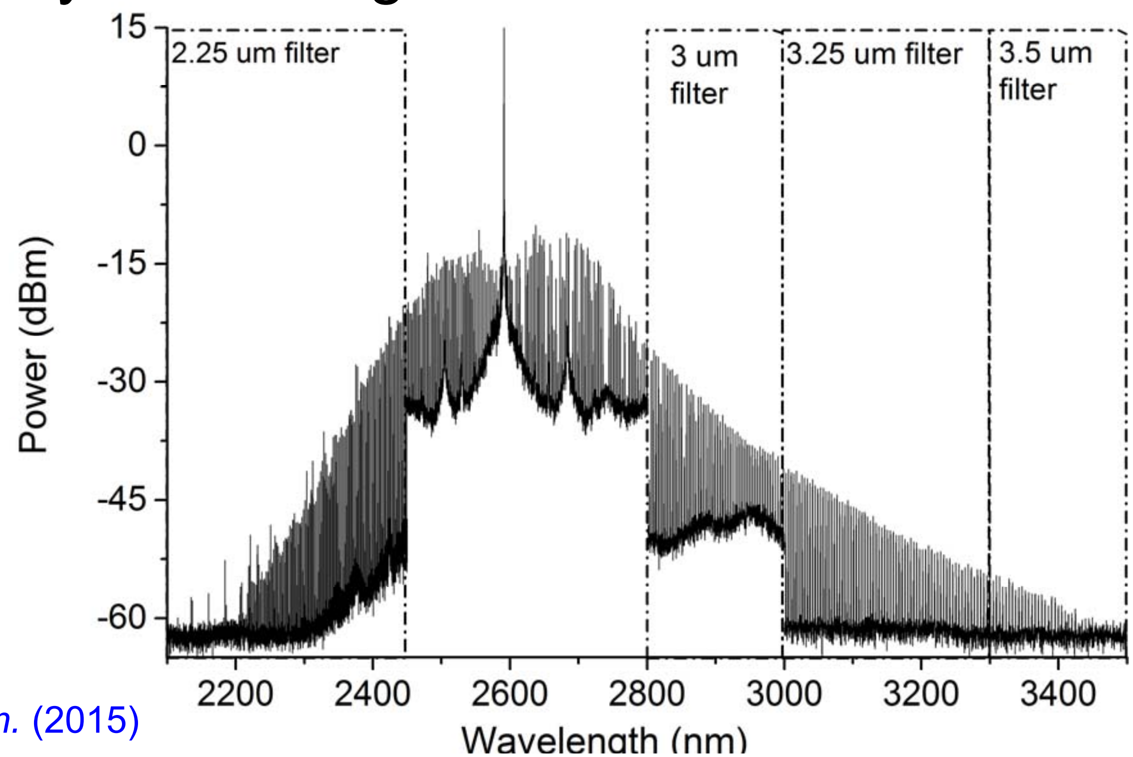
Luke, et al., Gaeta and Lipson, *Nat. Comm.* (2015)

Mid-IR Parametric Frequency Comb in Silicon Microresonators

- 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)